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Global Warming and System Safety

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ABSTRACT

We are currently confronted with the existential challenge of global warning. Because of its nature it is a challenge that confronts the entire globe both in terms of contributing factors and bearing the consequences. In both aspects there is an inevitable balance of responsibilities and consequences. In the former, some national entities are bigger contributors to the problem than others and in a similar manner some global areas suffer relatively more significant negative consequences. Another major challenge has been that of generating a better scientific understanding of the relationships between greenhouse gas emission, global warming, and the resulting environmental consequences. The remaining challenges that follow are how best to prevent or minimise greenhouse gas emissions, how to store them safety and how to mitigate the potential negative consequences. These are now global level responsibilities. At first sight this appears to be a problem restricted to big science, technology, and engineering alone in terms of finding more acceptable forms of energy production, as a counter to our current dependence on fossil fuels and that it might not be an area where system safety can play a prominent part. However, this is not the case, and this paper explores the system safety application possibilities, because all new developments require to be implemented in a safe manner.

INTRODUCTION

The world is currently facing an existential threat as a result of global warming. The seriousness of this problem was recently aired for all to see at the global COP26 meeting in Glasgow, UK in November 2021. The debate about global warming has had a chequered history, which has broadly followed the lines of: It is not really occurring it's a scam. It might be occurring, but this is a normal part of the natural earth cycles. Human activities are not a significant cause. Human activity does appear to be a significant contribution. To cut a long story short, the science has now overwhelmingly demonstrated that global warming is in fact occurring with human activity a prime cause through harmful greenhouse gas emissions, Figure 1. This trend has significant negative consequences for society in the global sense (for example Figure 2). Of course, there are many industries whose commercial success is based on energy production from fossil fuels, which presents the major source of greenhouse gas emissions. There are obviously major conflicts of interest in the challenge of tackling global warming between commercial interests and those parts of the world which bear the greatest environmental risks.

Figure 1: A Primary Contributor to Global Warming

Traditional System Safety has a long history of safety applications, safety assessment methodology, risk tolerance standards and established criteria. It is now accepted as one of the critical requirements for ensuring the success of any industry. System safety will be intrinsically linked to the nature of the technology to which it is being applied and how to remove or minimise such risks down to generally accepted tolerance levels. That is, they are generally no more significant than those suffered from other sources.

Of course, there is always a difference in what is meant by the implementation of safety and the resultant assessment of remnant risk. The former relates to the application of positive measures and constraints to achieve safety and the latter provides a best effort measure of how successful the applications appear to be. The former is primarily related to the application of sound principles which gives a sound basis for safe technology application, ensuring the products, human involvement, associated processes, and usage will be acceptably safe. Making safe is essentially based on fundamental arguments and the application of clear common sense, but this has become more and more difficult to ensure as products and processes become more complex and less transparent. In turn, risk assessment follows from our *best attempt* at qualifying or quantifying such, based on the level of completeness of our knowledge underpinning such assessments. This also continues to challenge us as technology becomes more and more complex. We can never claim complete knowledge and detriments (a penalty or mishap) can still occur as a result of incomplete knowledge, in addition to failure to follow established rules or best practice.

We have also been aware, over many decades, that human harm can occur through harmful alteration of environmental and geological conditions, whether they be naturally caused (e.g., volcanic, earthquake) or through human based process (for example in the 1960s/70s the UK smog problem caused by domestic coal fires, and the radioactive material release from the evolution of the nuclear industries). These latter concerns have led to environmental protection standards and proactive safety monitoring for standards compliance - regulation.

Global warming gives rise to an evolving need for environmental protection but on a global scale and where the cause and effect (the individual cause contribution and where the effects occur) are not easily understood without the application of state-of-the-art science. As noted above, this subject area has passed through phases of doubt, scepticism, uncertainty, and lack of direct evidence. But eventually through mounting scientific evidence and increasing examples of the detrimental consequences, it has become clear that the problem is real, existential in nature and with a major human based causation. We are already seeing substantial direct evidence of the detrimental consequences.

So, what part should system safety play in this subject area, what guidelines should be developed, and should system safety be involved in the establishment of criteria and standards and in what form should they take for enterprises which may be judged as major contributors to global warming, and protection of those who are at the greatest risk.

CONTRIBUTORS AND NON-CONTRIBUTORS

Unlike the more general case where most if not all enterprises have a major stake in the prevention of detriments relating to the design, manufacture, and application of their products, the same is not broadly so for global warming. In this case a more limited number of enterprises are responsible for the major risk contribution, and at first sight it is unclear how the normal processes of system safety can impact on mitigation of the problem, but system safety does still have a role to play, but by more of an indirect nature. Reduction in the quantitative nature of greenhouse gas release will take the form of new technologies for energy production, the application of new more environmentally friendly energy sources and the potential for their greater general application. Many

Figure 2: One of the Detrimental Effects

take the form of already technically available alternative sources, which in principle, do not significantly contribute to greenhouse emissions. These will need to be scaled up with the necessary technical advances to become more commercially viable. Nuclear power is a major example. Cases are currently being made for an enhanced application of nuclear power with new reactor designs, including the alternatives of small modular forms. In the long term, this might even extend to the eventual practical application of nuclear fusion. Other viable alternatives for expansion are based on directly harnessing solar power through enhanced focussing, solar cells technology, and harnessing the winds and tides. These can all ultimately supply domestic, commercial and transport applications. In the latter case alternative sources of energy are already taking the form of high energy density batteries and the potential application of hydrogen cells, all being technically feasible but needing development to extend their coverage in a more commercially viable and efficient form.

The core of these 'developments' will be based on advances in science, technology, and engineering, but no matter what form all will introduce new detriments and risk and, as such, all will require the skills of system safety to identify the detriments, the potential paths to such detriments, together with an ability to find and implement solutions to remove or mitigate risks to acceptable levels.

For example, the case of nuclear fission is already an area where system safety has played a prominent role and will continue to do so especially if this industry is poised for expansion with new technical approaches, which will need to be assessed for safe implementation. The same will inevitably apply to the other new or expanding energy supply sources, which will replace fossil fuels and to the parallel case of new and expanded greenhouse friendly transportation power application. In all cases, the new technologies and methods of application will give rise to new safety challenges and the need to overcome these leading to acceptably safe operations.

The bottom line here is that although system safety may not be a big player regarding the enhanced methods for reducing greenhouse emissions it will be in terms of the safe applications of the new approaches. In addition, the same can be said in principle about those new techniques being developed for the capture, application of and safe long-term storage of greenhouse gas emissions.

WHAT IS A GREENHOUSE GAS?

Greenhouse gas emissions are the fundamental cause of global warming. They are gases that absorb and emits radiant energy within the thermal infrared spectrum, leading to the capture of heat leading to increasing temperature. The principal greenhouse gases in our atmosphere are water vapour, carbon dioxide, methane, nitrous oxide, ozone, and other fluorocarbons, where through quantitative measure of release criterion, carbon dioxide is the major concern. These can have beneficial or deleterious effects. For example, without greenhouse gases in our atmosphere the average earth's surface temperature would be about -18C and this of course would make human life uncomfortable to say the least. Ozone also has a beneficial aspect in that it helps to protect the earth and life from harmful ultra-violet radiation. At the other extreme Venus, which has a major content of greenhouse gases in its atmosphere, has a surface temperature of many hundreds of degrees C. It is hotter than Mercury, although the latter is significantly nearer to the sun. Additional greenhouse gases in our atmosphere will move us in the general direction of Venus. Or course we are not talking about Venus scale changes, but current science tells us that average temperature increases of the order of 1-2 C above pre-industrial levels can still produce local and global catastrophic conditions with increased frequency. Science now confirms that we are moving in this direction, and this is confirmed by direct experience. Without rectification the situation will continue to get worse, with the additional concern that cliff-edge conditions may ensue. The current trend of increasing greenhouse content will lead to ever more powerful storms, increased rainfalls, mudslides, increased melting at the poles and other icefields, increased rise of sea levels, increased flooding, increased droughts with more extensive fires and more areas of the earth turning into desert conditions. Science has now made it clear that human activity is a major cause of this increasing greenhouse effect and humanity must be responsible to reverse it. The greenhouse gas increases are essentially occurring because of humanity's greater and greater need for energy and the current reliance on fossil fuels, such as coal, oil, and natural gas. So, the challenge is now to move to more environmentally friendly energy sources, coupled with more efficient processes for greenhouse gas capture and safe storage. In the latter aspect, the world is also currently moving in the wrong direction by continuing to reduce the global capacity of carbon capturing vegetation (forests).

SAFETY AND RISK IN THE GLOBAL CONTEXT

SOME OF SYSTEM SAFETY 'DIFFERENCES'

Any venture of system safety into global warming takes one inevitably away from the more locally related responsibility for detriments to a world of distant partial contribution to detriments with no simple direct relationship between individual cause and effect.

The more traditional system safety world relates to somewhat 'local' boundaries within which, cause and effects occur, and where responsibilities more clearly lie, based on the known manufacture and usage of products. This also applies to the case of the more traditional aspects of environmental protection, where the responsibility is clear, and the detrimental consequences are usually restricted to defined and more limited boundaries. Of course, there are exceptions even here, where detriment boundaries can by quite large. For example, nuclear power and nuclear weapon industries, where catastrophic failures can be far reaching but where the responsibilities are clear, and the boundaries can be assessed. Perhaps a more nebulous area in relation to boundaries and responsibilities is exemplified by the current COVID -19 pandemic, where the boundaries are indeed global, and so are the causes and effects but there is as yet no clear accountability.

Global warming boundaries, simply by their definition, are indeed global but there is, and must be, a shared responsibility for causation. The suffering is not globally uniform, and those who suffer from the worst consequences, are not necessarily those causing the problem. As such, the latter will not necessarily have the most powerful resources or powerful voice in ensuring mitigation or removal of the problem. In addition, those enterprises which are the greatest contributors to the green-house emissions will see their industries as key elements of their economy, both at company and national level, and as such will be somewhat resistant to the pleas from the most affected areas of the globe. This self-interest represents a major challenge to an early rectification of the problem.

In turn, apportioning and acceptance of responsibilities and accountabilities by individual countries and enterprises is likely to be confrontational in nature and not an easy task to solve. Especially in the current climate, where individual enterprises have major dependence on fossil sources as their prime source of energy for domestic, industrial and transport applications and indeed where it often forms a key element of a country's economy.

BENEFIT AND RISK

In the case of global warming there will be risks, but not in the conventional form. In this case the additional risk relates to the distributed global elements and is uneven in nature and is difficult to qualify or quantify in the usual sense. Traditionally a single enterprise can establish a conventional benefit/risk balance simply by just considering the local elements of risk associated with its local activities … it bears its own risk responsibility. For example, how does it benefit the enterprise and the customer base it supplies and what risk arises from its own operations and for the customers' use. In this greenhouse gas world, the process for estimating benefit follows the usual lines but the risk is somewhat more nebulous, in the sense that an enterprise cannot easily estimate its contribution to the global nature of the detriment risk. Hence, individual risk responsibility is difficult to define and quantify in this case. It is the overall emission which causes detriments, and there will be no clear and deterministic relationship between a specific detriment and individual enterprise contribution. At this stage it appears difficult to move far beyond the relatively coarse measure of a nation's relative contributions to the global emission. In addition, the relationship between overall emission and the full range of potential detrimental consequences that might occur is by no means fully understood. Current environmental scientific assessment indicates that one should ideally aim not to exceed an average temperature rise of 1.5C above the pre-industrial level, with major global concerns arising for increases of 2C or more. Many enterprises will be minor contributors and any attempt for further minimisation will be more for moral/PR purposes only, and in line with some general national expectation to do better. The situation will be different for major emitters and these enterprises will be subject to both global and national pressure to look for significant reductions and for compliance with any agreed standards that ensue. The global pressure will inevitably be governed by the proportionate size of the national contribution to overall release. Another risk, or loss of benefit that is already becoming a reality in the cost benefit balance is the so-called carbon tax. Both emission reduction and reduction of carbon taxes will appear in the overall benefit /risk balance

ANOTHER ASPECT OF RISK

A complete process of defining and measuring global warming risk, is itself a very complicated business. Of course, the obvious starters were noted previously as more frequent and greater storms, increased flooding, and increased droughts, etc. But these are simply the first stages of the detrimental consequence. From these will flow a whole range of subsequent detrimental consequences, such as loss of food production, new or more extensive diseases, disruption of transportation, loss of habitable land, starvation, increased international, national, or local tensions, loss of viable areas for occupation, mass movement of populations, etc. These are not typically the areas where system safety activity takes place in relation to risk assessment but nevertheless may still benefit from the logical mode of thinking normally embedded in system safety.

A HIGH CONSEQUENT RISK

Global warning does indeed fall into the high consequent risk category. However, it represents a difference to our normal experience of high consequence risk analysis and assessment where the probability of occurrence is small but is still subject to uncertainty – high consequence low probability. This has been, and still is, a difficult area for assessment and especially in terms of risk quantification. This is certainly true for the quantification of risk in the nuclear weapon enterprise for the worst-case consequences of inadvertent nuclear yield (INY) and inadvertent radioactive (RA) dispersal. High consequence risk is also associated with 'Black Swan' thinking, where the nature of the potential catastrophic consequences has not really been identified and of course with little ability to assess their probability. If we go back some decades, even global warming and its consequences were still not on the horizon, either in terms whether it could lead to an existential threat or whether there were any substantial grounds for estimating the probability of occurrence. In fact, global warming can be categorised as a 'Black Swan', and like all 'Black Swans' it has occurred with a certain amount of surprise and alarm. It is now certainly recognised as of very high (even existential) consequence, and the full nature of the spectrum of consequences is only now beginning to reveal itself. Consequences have already led to major human detriment, but the prognosis is that there is worse to come – perhaps a still evolving 'Black Swan'. This appears to be true even if greenhouse gas content does not increase above the present level and of course this will be exacerbated if content continues to increase, perhaps with still a lack of clarity of the eventual nature and scale of such consequences

ALARP IN THE GLOBAL WARMING CONTEXT

In the UK at least, risks are subject to the As Low As Reasonably Practicable (ALARP) test, which in fact is a Legal Requirement. This states that there should be a continual process of risk reduction until a stage is reached when the cost and effort is disproportionate to the risk reduction achieved. A clear evidence-based case must be made to substantiate this claim. This approach is associated with a Basic Safety Level (BSL) above which the risk is deemed as not tolerable and a Basic Safety Objective (BSO) which represents a viable aim for a risk level which is small compared with other risks in life. Essentially, the region between the two levels is identified as the ALARP region and where most of the ALARP assessment process takes place. It is assumed that most countries have a similar general strategy of this form. However, how this may be applied to global warming is somewhat challenging. Where partial cause-and-effect relationships for risk 'at a distance' are somewhat unclear and contentious, let alone having any sound quantitative and legal basis. It is not clear at the present time, how such a strategy of this nature could be applied even in skeletal form, given the difficulty of apportioning (and the acceptance of) responsibilities to the overall global contribution and to local specific detriments. Nevertheless, some strategy and framework based essentially on the ALARP concept does appear to be a valid aim for such enterprises and particularly those classed as major emitters.

THE BOWTIE SAFETY CONCEPTS

In the grand scheme of things traditional safety approaches are based both on the Swiss Cheese and Bow Tie concepts of prevention of detriments and limiting their consequences. That is, minimising the probability of a sequences leading to potential harm and following this by actions to mitigate the level of the detrimental outcome. This approach can also be applied in principle to global warming in terms of limiting the potential for emissions and taking further precautions for mitigating the level of consequence. The latter can take the form of early warning of impending abnormal environmental conditions, better protection against flooding, reduced potential for fire damage and even processes for safe capture and safe geological lock down storage through enhanced technical means There is a precedent for the latter as exemplified in the nuclear industries in the handling and storage of nuclear waste. However, this example has not been a process without its difficulties… but lessons may be learned here. Although the core elements of this subject area are mainly associated with meteorological, hydrological, and geological sciences and engineering, system safety assessment methodologies will still have a part to play.

THE RELEVANCE OF TRADITIONAL SAFETY ASSESSMENT TECHNIQUES

The question arises as to whether the safety assessment methodologies developed in system safety still apply to the risks associated with global warming. In general, they still appear to be, given suitable customising. For example, the top-down Fault Tree Analysis (FTA) approach can be applied at enterprise level, where the tops of the trees will list emission types and quantities. In turn the fault tree analysis can be used to identify the contributing sources to the top-level emissions. This can then be used in the usual way to identify the main contributors and where best effort should be focused to remove or minimise these.

Failure Modes and Effects Critical Analysis (FMECA) can also be used for assessment in an upward direction to assess the emission implications of fault occurrence. As part of this whole process, associated FTAs can be applied in the downward direction from the fault in order to identify the more fundamental reasons for the fault occurrence and the potential sequences that gives rise to such faults, so that mitigation action can be appropriately targeted. From a general perspective, it would still appear that the safety assessment approaches developed for system safety, should play at least some part in the reduction of the greenhouse risk. Although, these will not play a significant role in reducing or eliminating emission from a normally operating fault free process. The latter can only be done through fundamental changes in approach and the associated application of new technologies and where system safety can play a more traditional role.

The whole subject area of global warming, greenhouse gas emission, safe storage possibilities and societal consequences, does look like a subject that would benefit from the holistic approach of System-Theoretic Accident Model and Processes (STAMP) advocated by Nancy Leveson of MIT. Its more universal overarching approach for all possible detriments and all possible causes would seem to be ideally structured for wide-spread risk analysis needs of this type.

INVOLVEMENT IN TRADITIONAL RISK ASSESSMENT

All enterprises which have an element of detriment associated with products, their manufacture and use will, as part of their interests and responsibility, apply traditional system safety assessment methodologies as part of normal operations. However, this will not necessarily be true in relation to Global Warming case. Some enterprises will, by their very nature, have a minimal contribution to such emissions and as such application of traditional assessment methods may only be for good moral/PR reasons. However, at the other extreme there will be enterprises which will be major contributors, and in this case appropriate new approaches and technology application will be necessary to minimise emissions. The traditional system safety approaches will be directed to the safe implementation of these new approaches and technology applications. This will open up a whole range of work areas for system safety.

WHAT ARE THE RENEWABLE AND ALTERNATIVE ENERGY SOURCES?

All sources of energy ultimately come from the sun. Even fossil fuels were 'manufactured' by solar energy at some stage during the earth's history. The renewable energy sources are broadly; solar, wind, hydro, tidal, geothermal, biomass, where in some cases the potential energy available is related to geographical/geological conditions, time of year and even time of day. These latter aspects raise the need for efficient and large-scale technology approaches for energy storage and major release when required because of the 'transient' nature of its generation. All of these do not directly result in greenhouse gas emission, although the biomass case has been challenged in terms of its zero-carbon net emission claim. In addition, there are other forms of energy production which are not renewable but result in little or no greenhouse gas emission, such as nuclear fission. Other sources of energy such as chemical rechargeable batteries, hydrogen and hydrogen/fuel cells do not of themselves lead to harmful emissions, but fossil fuels are often the prime energy source used for their manufacture and recharging. Perhaps the holy grail for clean energy production takes the form of nuclear fusion. However, there are still substantial challenges to its success despite many decades of expensive international research and which is still only just at the energy break even stage. Even then further major challenges remain in the transition to practicable power reactors.

Whatever its form, it will involve significant levels of energy and power, and as such will be associated with potential high-level safety consequences and will have to be handled in appropriate way. This is certainly a business area which calls for, and should apply, system safety skills. In the following sections, the arguments are centred around the human risk element, but of course there will also be the parallel detriments related to commercial cost, continuity of supply, reputation, etc.

NUCLEAR FISSION POWER

Although the nuclear power industry has not had a historical smooth ride, because of major accidents and the need for safe decommissioning and handling and storage of nuclear waste, nevertheless the current climate will look again towards its expansion as a low greenhouse gas primary energy source with a continuous 24-hour a day character. System safety can play a major role from two perspectives.

1) Enhancement of confidence to allay the concerns which are traditionally raised about this technology.
2) With the extension of its application and in relation to the development of new design concepts and technical approaches.

Nuclear power will always have its major safety critics, so enhancing the safety case quality and preventing mishaps will be strong elements in supporting its extended use. Stronger system safety involvement is obviously a core element in achieving this. In the second aspect it goes without saying that the introduction of fundamentally differing concepts and new technologies *must be accompanied* by a major application of system safety. Here we will be talking about true system level changes and the need for an associated system level approach for ensuring safety in what is truly a high consequence industry. One newly developing area where this applies is in the burgeoning interest and development activities associated with small modular reactor designs which offer the opportunity for distributed siting for targeted energy requirements or aggregation in central locations. Developments lie in the fields of Light Water (LWR), Fast Neutron (FNR), Graphite Moderated High Temperature (GMHTR) and Molten Salt (MSR) reactor technologies. These are suggested to have several advantages over more traditional approaches; more easily factory built, more passive safety, small radioactive inventories, more protective and easier siting, easier decommissioning. This spectrum of potential new developments provides many opportunities and needs for system safety work, covering development programmes, subsequent certification, and routine operation. This could be a provide a long-term intensive system safety involvement.

The nuclear weapons industry on the other hand, although critically dependent on system safety approaches, is not a significant contributor to global warming. Its remanent contribution will essentially be based on taking a responsible attitude by limiting and making more efficient use of its energy consumption.

Nuclear Fusion Power

There is a long history of R&D work in this area, for example 80 years for magnetic fusion approaches and 50 years for alternative laser inertial approaches. But, even after this long time only relatively dubious claims of achieving breakeven conditions have been made, exemplifying the extreme scientific and technical difficulties associated with this type of research. Major national and international programmes are underway to harness this form of energy in a safe and manageably way. For example, magnetic controlled plasma fusion (Tokamaks) in France (ITER), UK (JET), Italy (DTT) and Japan (JT-60SA), where this approach currently appears to be the most promising one. The main alternative is in the form of high-power laser inertial confinement fusion (ICF) of targets, both in indirect and direct forms. Major national and international programmes are underway in the US (Omega and NIF), France (LMJ), UK (Vulcan and Orion), China (SG-II and SG-III) and Japan (GEKKO- XII). The follow-on process to a practical fusion reactor still looks unclear. However, claims have been made to suggest that this technology will provide modest supplies to the electrical grid in the 2030s, becoming more widespread by the middle of the century. No doubt global warming will give an extra push in this direction, but previous claims have always been somewhat optimistic. Again, because of the large energy and power associated with these programmes, system safety thinking is essential to avoid catastrophic failure. The only system safety role in the near future would be one in supporting major physical experiments rather than in what is the more traditional role of product manufacture and application.

Wind and Tidal Power

Both will involve the application of and expansion of current or enhanced technologies, in what can be hostile environments. Both rely on environmental forces as the prime source of energy for electrical production, but both may encounter challenging hostile extremes leading to increased technical risk. During normal running, neither will have extensive human presence at the point where the environmental energy to electrical transduction takes place. However, the major electrical loads need to be handled in routine system safety fashion at the receiving and distribution base, where human presence exists at least for monitoring, control, and maintenance aspects. Installation, maintenance, and repair involve human activity at the energy transduction sites and can be a cause of significant human risk and where system safety skills will play a significant role.

Hydroelectric Generation

This is an already well-established technology area but like the case for nuclear energy, there will be pressures to extend its application, where geographically viable, because of global warming. What had previously been seen as inappropriate or uncommercial possibilities will be re-looked at and given a greater incentive to develop and apply more efficient and cheaper approaches. Such extensions and new developments will not occur without the presence of new or enhanced risks. Again, the human element of risk will be mostly focused on the implementation, maintenance, repair, and control activities associated with such major engineering enterprises. Because of the site’s scale and the large sources of energy involved, unsafe operation can result in major negative consequences. Not only at the site of a dam but also down- stream, should a catastrophic failure occur. As such, system safety has and must continue to play a major role.

Direct Solar Energy

There are several possibilities here but the two for which most activity is currently focussed on are solar cell technology and light concentration. Both can be applied in centralised or local distributed fashion. In its more centralised form, there will inevitably be large levels of electrical power and energy storage, which will always pose the most significant risks to human health. As these installations grow in size and capacity so will the scale of potential consequences, requiring the need for a matching systems safety approach to manage these risks in an acceptable safe manner.

Of course, there have also been space-based collector versions in this category, but this lies outside the scope of this paper.

BIOMASS

This method of energy production is claimed to be carbon neutral. Unlike coal, oil, and natural gas, where the carbon was previously geologically 'locked up', and where its burning makes a permanent net carbon increase to the atmosphere, burning of biomass is claimed to be different. Biomass burning is claimed to be carbon neutral in the sense that the CO_2 produced is naturally re-aborded by vegetation giving no net carbon increase to the atmosphere. The associated argument is that that unburned waste wood would naturally decay and release its carbon back into the atmosphere anyway. So, the claim is that a carefully managed overall process even if not strictly zero carbon, would still be a far less net carbon emitter than fossil fuels. The degree to which this statement is correct is still somewhat contentious, based mainly on the rate at which carbon is re-absorbed in relation to the scale and rate of release by burning. The former may not compensate for the latter. Again, as installations become more expansive and burning takes place on an industrial scale, this will pose major potential hazards which will continue to need safe management.

TRANSPORT SYSTEMS

These are systems which are energy intensive users and as such are major contributors to greenhouse gases, given their current heavy dependence on fossil fuels. The prospect of and the rate of change in application of alternative sources will depend on the transport type.

AUTOMOBILES

The automobile industry is already well on the way to replacing oil fuel usage with rechargeable electrical battery sources and potential hydrogen fuel cells. This is already making a significant impact, although both approaches rely on external sources of energy to manufacture critical components and to power the recharging processes. Both approaches are bringing along with them new technologies and new safety challenges, which will require system safety scrutiny to identify and manage appropriately. Not only are these risks associated with workers in the associated industries but more so for the general public at large where automobiles are a domestic and industrial necessity.

AIRLINES

Another major greenhouse emitter are civil and military aircraft, again centred almost exclusively on burning oil. At this point it is pertinent to point out that it was pioneers in this industry who originally foresaw the need for a new and better System Safety approach to combat the dangers associated with flight. In fact, these people were instrumental in the original formation of a group of like-minded thinkers, which eventually led to the formation of what is now the International System Safety Society. There is no reason why the system safety approach, which already has a proud record of contributions in this industry, will not continue to be a major player in aircraft safety. Unlike the automobile industry, the application of revolutionary new forms of propulsion energy is still very much in the exploratory stage and may take the form of an adjunct to the traditional oil-based fuel. The application of liquid hydrogen, fuel cells, solar cells and rechargeable batteries are still at the tentative exploratory stage. The continuing exploratory path to more efficient use of cleaner fuels, through the introduction of new technologies and approaches will again introduce new risks which will need to be managed and where safety failure can be catastrophic. System safety will continue to have a prominent role in this industry.

MARITIME

The potential for greenhouse gas reduction here lies somewhat between the automobile and airline potentials. In addition to traditional oil, and of course in the past coal, alternative propulsion approaches are already established in somewhat specialised areas both in terms of nuclear and rechargeable batteries forms. Currently, these are almost exclusively applied to military systems both as primary and adjunct applications. The prospect for using hydrogen as a basic fuel also appears more feasible/practicable than for the airline case. In addition, sea transport can in principle take advantage of the environment it operates in … both from wind and 'tidal' energy. In the former case not only as an adjunct in the traditional sail form, but also by using the motion-based wind effect to generate turbine-based electrification. In similar fashion motion through the water can be applied similarly. Of course, these latter approaches will be subject to the fact that extracting energy in this form will introduce a penalty to the efficiency of the main propulsion element of the vessel. So efficient application will be critical. There are many cleaner energy alternatives for the maritime sector, each raising its own requirement for safe application.

CONCLUSIONS

It is now clear that we have a global level existential safety problem where all the science indicates that human activity is playing a major role in creating the problem through the increased rate of fossil fuel burning. As such, globally we should be accountable for finding solutions to combat the problem. We are already beginning to see the detriments that arise from global warming, as witnessed by the continuing reports of increased frequency of more severe environmental conditions. These take on the form of; storms, droughts, increasing deserts, melting of icecaps and glaciers, flooding, increased sea levels, etc. These all gives rise to serious impact on the health and well-being of the human race. These extreme conditions are predicted to get worse, even given the current level of global warming, whereas further increased levels of greenhouse gases in the atmosphere herald an even greater frequency of more severe eventualities. These concerns, by their very nature, are already producing both international and national action to look for solutions to prevent their escalation. The response will be in the form of changing our prime energy sources, methods of application and storage, new applied technologies, and efficiencies of usage, in order to minimise our reliance on and the impact of burning fossil fuels.

Although being an existential science and technology scale problem, it nevertheless presents an expanding opportunity for those engaged in the application of system safety, given the new technologies and engineering processes that will be developed. A whole new world of opportunities, or perhaps more correctly needs, will open up for those with these skills, noting the scale and urgency of the needs which confront us. The content of this paper has only scratched at the surface of where these opportunities and needs will arise. Certainly, a greater consideration of this subject area will be appropriate to more fully scope the opportunities and needs. It is also a time and opportunity for system safety practitioners to be more proactive in self-advertising and stating the crucial role they can play in the inevitable new safety concerns that will arise. In a similar vein, this is also an opportune time for the International System Safety Society to advertise its *key* contributory role in the safe solution to the new problems we face.

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Malcolm Jones, Ph.D., F. Inst. P., C. Phys., C. Eng has previously led the Distinguished Scientists group at Atomic Weaponds Establishment (AWE) and held the positions of Scientific Adviser to AWE's Chief Scientist and to AWE's Chief of Warhead Design, and currently supports AWE's Chief of Product Assurance. His career at AWE has taken him through a wide range of scientific and engineering topics, but he has maintained a continuous association with nuclear weapon design and process safety and top-level nuclear safety standards. His interests extend to corporate safety cultures and the root cause reasons for failures. He is a Fellow of the International System Safety Society, is a past winner of its Professional Development Award and is an adviser to a number of senior UK Ministry of Defence and AWE safety bodies. He has been awarded an MBE in the Queen's Birthday Honours List for contributions to the UK defence industry and is a recipient of the John Challens' Medal, which is AWE's highest award for lifetime contributions to Science, Engineering and Technology. He has also been honoured by VNIIA in the RF for his work in fostering nuclear weapon safety collaboration between the UK and the RF.