Life Cycle Assessment: Green Rocket Fuel

Heather Henry
March 10, 2009
ISU – Personal Assignment 2009

Acknowledgements

I would like to acknowledge and thank the following people for their help in completing this document. Without their support this would not have been possible.

Dr. Walter Peeters	International Space University Strasbourg, France
Dr. Roger Lo	Aerospace Institute Berlin, Germany
Nathalie Meusy	European Space Agency Paris, France
Christophe Abrassart	European Space Agency Paris, France
David Vivanco	European Space Agency Paris France

Table of Contents

List of Acronyms

EMD	Environmental Management Division
EPA	Environmental Protection Agency
ESA	European Space Agency
GHG	Green House Gas
ICBM	Intercontinental Ballistic Missile
ISO	International Organization for Standardization
Isp	Specific Impulse
ISRO	Indian Space Research Organization
JAXA	Japan Aerospace Exploration Agency
LCA	Life Cycle Assessment
LD50	Lethal Dose for 50%
LH2	Liquid Hydrogen
LOX	Liquid Oxygen
NASA	National Aeronautic and Space Administration

Abstract

The increasing need for sustainability has lead to policy changes and environmentally friendly engineering solutions throughout the space sector. What is needed now is a way to quantify these solutions in a way that promotes sustainability throughout the industry. Specifically, in the area of propulsion where 'green' fuels are being developed and tested, guidelines are needed to make and quantify this progress.

This paper discusses the Life Cycle Assessment (LCA) approach in sustainability as it relates to rocket fuel. It outlines the need for the development of such a system to help the space industry in qualifying the complete environmental impact of the use of a given fuel. As a comparison, the automotive industry is used because of its use comprehensive use of LCA analysis in environmental evaluation of both fuels and vehicles. Acknowledging the challenges unique to the space industry, this paper also addresses how sustainable engineering could contribute to the life cycle development of green fuel.

Due to the critical role played by fuel during a mission, any new sustainable fuel must first meet high reliability and performance standards. The challenges of testing and validating launch fuel are discussed and the impact that this would have on the development of green fuels is outlined.

To allow for the development of green fuel in a more productive and unified fashion the LCA is a suggested approach. The use of LCA for rocket fuel is concluded to be a good method for helping to guide the design of environmental objectives and for comparing the overall environmental impact of fuels.

Introduction

The environmental movement has been growing for several decades. This movement is changing, away from 'quick fixes' and local impact assessments, to a global initiative where behavior patterns are being analyzed for sustainability. The goal is not to only to undo the environmental damage that has been caused but to develop practices that will minimize the future impact. The push for environmental changes is both political and industrial. Global industries are changing their practices not only to meet the new environmental requirements but also as a means of appealing to their customers. The idea of 'going green' has increased economic value becoming not only a sensible course of action but also a social trend.

The Environment and the Public Space Industry

Within the public space industry, the environmental movement is also progressing towards more environmentally friendly practices. Agencies, such as the European Space Agency (ESA) and National Aeronautics and Space Administration (NASA), have begun to set up specific divisions aimed at monitoring, regulating and decreasing the environmental impact made by their agency. Another approach of environmental monitoring, being used by the space industry, is the adoption of the International Organization for Standardization ISO 14001 standard on environmental management. As an example, Japan Aerospace Exploration Agency (JAXA) is currently openly supporting ISO 14001 and has a published list of centers and departments that are certified.

Not all space-fairing countries have adopted environmental policies. Nations that are recent players to the space sector are not as focused on pollution and environmentally friendly practices. One reason for this could be that the starting point for most countries developing space technologies relies on techniques that have been used in the past. This leads to less environmentally sustainable products cycles but cheaper and faster development. An example of this is rocketry and launch vehicles. Historically, countries have developed their ability to launch objects into space based on the rocketry of old inter-continental ballistic missile (ICBM) designs. These designs did not take the environment into account. Existing technologies must be used, at least initially, regardless of environmental impact because getting to space is very challenging even when using available technology. Initially it seems that engineering challenges out-way the lack of sustainability in a project. This is true not only environmentally but also economically as seen in the US. Apollo project. Sustainability always comes second after first balancing cost, performance and schedule. The question now is, how much longer can we continue to change and destroy our environment before sustainable development will have to be considered before technological advancements.

Both an increase in public awareness and an increase in the political and economic incentives have contributed to the new push in making the public space industry more environmentally sustainable. Public environmental awareness has been a growing as the impact of decreasing oil resources, global warming, and world wide pollution begin to impact daily routines. As the public becomes more conscientious, the programs that are supported by public money must also become more conscientious. There is also a political and economic benefit experienced from environmentally friendly sectors. Programs that are more environmentally sustainable are also, in the long run, more sustainable in general because they do not rely on changing economic externalities (*e.g.* the changing prices of oil). These same programs can be made more publically popular and will thus have more political support resulting in continued or increased funding. Within the public space industry there is a need for public and political support. This could be achieved through the adoption of more environmentally sustainable policies.

To achieve a more environmentally sustainable public space industry, the industry itself must be divided and analyzed separately. The following sections will look specifically at the improvement of launch fuels. This aspect of the space industry has already undergone public criticism and serves as a good subject to examine the evolution of environmental changes that have taken place and that must take place in order to make space more sustainable.

'Green' Fuel – The Current Context

Historically the development of launch vehicles has used ICBM technology. This technology would usually dictate the fuels used and developed by the country. As an example, the US. developed solid rocket fuel because the technological know-how already existed in the country and therefore it was both cheaper and timelier to develop during the initial space race in the 1960s. Fuel criteria were based on two key parameters, thrust and specific impulse (Isp). This is graphically represented in Figure 1. Thrust is a measurement of force and Isp is a measurement of the efficiency of a fuel, the more efficient, the less fuel you need to carry with you. With political and public support now in favor of greener development, new criteria have begun to enter into the scene.

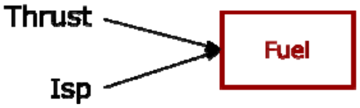

Figure 1: Engineering input parameters for the production of fuel

The initial search for greener rocket fuels can be linked to the automotive industry's search for greener car fuel. The social and political stage allows for increased research funding for fuels that have less of a negative environmental impact. For the automotive industry the aim is to find a fuel whose combustion products do no include harsh green house gasses (GHGs). While this is not the major concern for rocket fuels, it has allowed for the development of alternative rocket fuels that are less toxic and emit fewer ozone depletion molecules. The term 'green fuel' has been most consistently used in the space industry to describe fuels that adhere to environmental and toxicity standards. These standards have not been agreed upon leading to different perspectives in what is designated as green. A unified unbiased approach is needed.

The following section outlines the current criteria for the development of green fuel. The criteria discussed are environmental consequences due to launch and toxicity due to launch and handling. The environmental effects and potential effects of both criteria will be described. Finally, the problems with the current criteria will be identified and preliminary list of requirements for a new methodology in green fuel identification and criteria will be presented

Environmental Consequences

The direct atmospheric consequences of space flight are two fold; firstly, the release of rocket combustion bi-products and secondly the release of these bi-products in all layers of the atmosphere. Rocket plumes can be composed of particles (*e.g.* smoke, aluminum oxide and coke), water vapor, toxic gasses (*e.g.* CO, NO_2, F_2 and unsymmetrical dimethyl hydrazine), corrosive gasses (*e.g.* HCl and HNO_2) and aerosols. All of these have potentially damaging effects that can change the atmosphere behavior and composition (Rycroft, 2008)

The most well understood consequence of atmospheric pollution is the greenhouse effect, whereby molecules in the atmosphere trap incoming infrared radiation within the Earth's atmosphere. This effect is known as a global phenomenon because its consequences are not regional but rather worldwide. The release of these GHGs is caused by both natural and anthropogenic sources. It has been shown that the space industry has played a very small role in contributing to anthropogenic green house gas emissions. In 2008, 69 orbital launches were recorded. If 100 launches is assumed to be representative of today's launch activities the space industry is three orders of magnitude lower than that of air traffic. Even models that forecast an increase in the number of space flights, due to the growth of space tourism (increase to 1 million passengers per year) and full lunar development, still predict the GHG impact to be 15 to 40 times lower than that of air traffic. In scenarios where tourism and lunar development are more modest and realistic the effect is decreased by an order of magnitude (Lo, 2001).

Despite the minor global impact of the greenhouse gases exhausted from rocket fuel combustion, the effect of this exhaust on the local environment has been measured and is considered the more important criteria for determining environmental impact of a fuel. Based on the effects on the troposphere, stratosphere and ionosphere the changes are transient but it is still unknown whether even a modest increase of launch rates may create a lasting effects. Currently troposphere effects include local acid rain and high altitude cloud nucleation caused by the particulate material in the rocket plume. The number of chemicals that cause acid rain, assuming 100 launches can be seen in Table 1. The acid rain causing chemical in space launches is hydrochloric acid from solid rocket boosters.

Table 1: Acid rain sources taken from the US. in 1992 compared with 100 space launches

Source	Acid rain forming chemicals (Tg/year)
Heating and power production	33
Transportation	9.1
Industry	6.1
100 space launches	0.02

The effect on the stratosphere, which is where the ozone layer is found, is caused primarily from solid rocket fuels such as ammonium perchlorate. The infusion of a high concentration of chlorine molecules at this altitude leads to an 80% decrease of ozone within the rocket plume having a diameter of a few kilometers. This represents an average global decrease of less than 0.03% demonstrating that the effect is really a local one. The depletion of local ozone is also followed by a decrease in ionosphere. The ionosphere is an area within the atmosphere with a higher electron density. The cause of electron density reduction is due to the water vapor exhaust. The ability of water to improve the recombination of molecules creates a hole within the ionosphere (Rycroft, 2008).

Clean exhaust is a difficult issue to resolve because no molecule is really considered safe for passage through all layers of the atmosphere. Of course, some molecules are considered worse for the atmosphere environment than others, but when water vapor exhaust has negative effects, it can be seen that there is no such thing as a perfectly green propellant. Other consequences such as toxicity and ground pollution must contribute to further outline the criteria for such a fuel.

Fuels can also have a regional ground pollution effect. The affected regions are not only located at the launch sites, as described above with atmospheric pollution, but also the production sites. The affected area (*e.g.* water, soil) determines the range of environmental contamination. Ground, water and air environmental regulations vary dramatically from country to country. These regulations often take lots of time and effort to establish and thus are generally implemented only after significant amount of data, showing negative effects, have been gathered.

One example of a ground pollution effect that can be seen at the launch site is ammonium perchlorate. This chemical is used an oxidizer in solid rocket boosters and can cause ground contamination when it falls back to the Earth unburned. The environmental and health concerns of ammonium perchlorate are well known and studied in the United States. If mammals are exposed at high enough concentrations the perchlorate ion can disrupt metabolism by causing thyroid disorders (Urbansky, 2002). The U.S. Environmental Protection Agency (EPA) released a reference dose of 700 ng kg^{-1} day^{-1} is now at 32ng/mL in water (EPA, 2009). Currently there have been no attempt by the EPA to nationally regulate the allowable concentration of this molecule in drinking water, however, the awareness of the adverse effects of perchlorates have been widely spread in mass media and regions have begun to adopt their own policies. This shows that the environmental criteria push does not have to be at a national or international level to affect industry. Whether these policy decisions are from marketing, politics or environmental concerns, the space industry will have to conform. Oxidizers without perchlorates are now considered greener than those containing these molecules.

Toxicity Consequences

The toxicity of fuels is currently the second evaluation criteria for green fuels. This criterion is primarily in existence because the toxicity of a fuel is directly proportional to the storage and handling costs. The most obvious hazard is the spill of the toxins outside the production plants to harm ecosystems and adversely affect human health. To prevent this the many safety precautions must be taken increasing the training of the handlers, the costs of containment and an overall decrease in sustainability. (Accettera, 2004)

The toxicity of fuels is measured using the dose that kills 50% of the victims exposed (LD_{50}). The LD_{50} rating is not absolute and depends on the mechanism of exposure (*e.g.* dermal, inhalation, oral), the length of exposure (*e.g.* chronic, acute) and any sex specific effects. The measurement is normally in g/kg and has a general range as shown in Figure 2 (Lo, 2001).

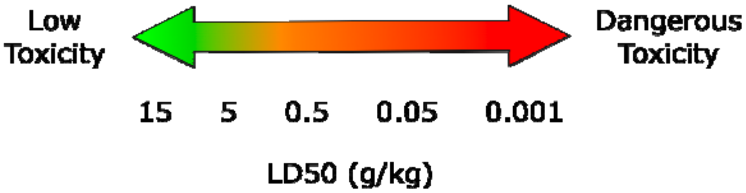

Figure 2: Chemical toxicity range

The toxicity hazard during operations and storage for handlers also plays a role in environmental sustainability. The increase in safety precautions consumes both time and money. Other fuel storage hazards include fire, explosion and corrosion. Again, the more difficult a fuel is to store the more money and time that must be expended.

Identification of a new approach

The current strategy to find green rocket fuel is to find a fuel that meets the minimum Isp and thrust requirements while also taking environmental and toxicity considerations. This is demonstrated pictorially in Figure 3.

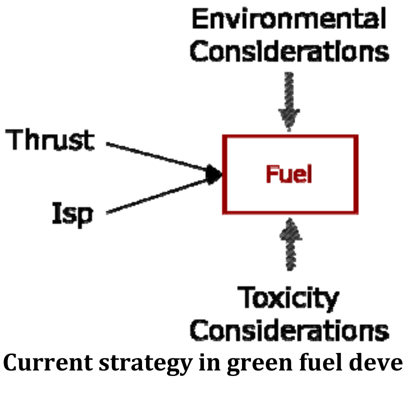

Figure 3: Current strategy in green fuel development

According to Haesler (2004), the ideal green propellant should consider the following elements:

- Toxicity: operational/handling hazards and safety precautions
- Pollution Impact: ground, atmospheric and space environment
- Cost: operational, transport and complexity (cryo-cooling)
- Performance: mass-specific and volume-specific on a case-by-case basis

While this approach considers some environmental issues, it does not consider all of them. For example, few studies have been do to compare the energy needed to produce, store and transport a given fuel. Without a holistic approach ranking fuels to determine how green they are is difficult. Often those fuels that are environmentally more benign, such as LOX and LH2, are complex to store. Similarly fuels designed with high Isp also have low thrust. There are multiple trade off factors that must be considered and a more well rounded approach throughout the product life cycle is needed if the best option is to be identified. This analysis can be used to create requirements for a different approach in green fuel.

A preliminary list of requirements is established in Table 2. These requirements are based both from both environmental concerns established for the public space industry and the industries need for an analysis tool that considers systems rather than just individual components.

Table 2: Preliminary requirements for a green fuel comparison methodology

Preliminary requirements
1. The method shall take into account the entire product life cycle.
2. The method shall use quantitative data as input in all available situations. (*e.g.* toxicity, energy requirements, pollutants, performance)
3. The method shall take into account financial and political restrictions.
4. The method shall output impact assessments for the space, land and atmosphere environment.
5. The method shall take into physical restrictions of Isp and thrust.

Life Cycle Assessment of Rocket Fuel

Life Cycle Assessment (LCA) is a tool that has been used for environmental impact assessments and is considered a good resource for sustainable development. It is a ‘cradle-to-grave’ approach that examines the entire life cycle. Through this assessment environmental impact indicators can be produced both on a regional and global scale. The LCA approach would make the overall environmental analysis of rocket fuel less biased and provide a means of truly decreasing the environmental impact. Already NASA uses the minimization of life cycle costs to minimize and correct for environmental consequences within the Environmental Management Division (EMD). The approach, in this case, would be making this approach more specific to rocket fuels.

LCA Strengths

The LCA approach is proven. The shift of cradle-to-grave analysis for environmental factors has been used in the automotive industry to successfully evaluate alternative fuels and alternative vehicles. Traditionally automobiles were evaluated using different carbon footprint analysis tools. The LCA analysis includes more than CO_2 output and toxicity measurements. It includes environmental factors such as energy consumption, all types environmental waste, and the input materials. A vehicle life cycle takes into account the vehicle design and development, materials extraction/sources, vehicle manufacture, vehicle use (including fuel production and distribution, service and maintenance and other fixed costs), and vehicle end-of-life. Before the LCA approach was applied companies could claim that their vehicle was more environmentally friendly due to single criteria alone (*e.g*. fuel mileage, type of fuel used) and the public was unaware of tradeoffs made during other parts of the products life cycle. By considering the entire lifetime of the vehicle including its end-of-use, the goal of this analysis in the automotive industry was to determine a global winner that excelled in every aspect of its life cycle. This was not the case. This does not diminish the validity of the LCA approach; instead it demonstrates the complexity of trying to analyze the environmental impact using only a few indicators and life cycle periods. The LCA would also make the true environmental problems of fuel more recognized and thus allow a more focused engineering design to appeal to these issues.

A SWOT analysis of the LCA method used can be found in Table 3. This table outlines the strengths, weaknesses, opportunities and threats if the LCA approach is taken for rocket fuels. All of the obstacles presented would need to be overcome if the LCA method were to be adopted.

Table 3: SWOT analysis of LCA for rocket fuel

Strengths	**Weaknesses**
• Takes multiples factors into consideration allowing for a complete comparison between different fuels • Based on the environmental impact issues and not politics • Provides standardization green fuel concept • Quantifies the results	• Complex models must be created • Solution may still not be clear • Time consuming process
Opportunities	**Threats**
• Improve public perception of the space industry's environmental responsibility • Allows space agencies to define a goal for their environmental impact and assess and track their progress	• Requires data from private industries on manufacturing details • Assumes chemical propulsion will continue to remain central to space propulsion

Using a LCA tool, green fuel could be better characterized and the environmental issues of each fuel better understood. The life cycle of fuel would include extraction, production, refining, handling, storage, transportation, and use as seen in Figure 4. Each of these processes would have environmental in and output parameters and could thus result in both localized and global environmental indicators.

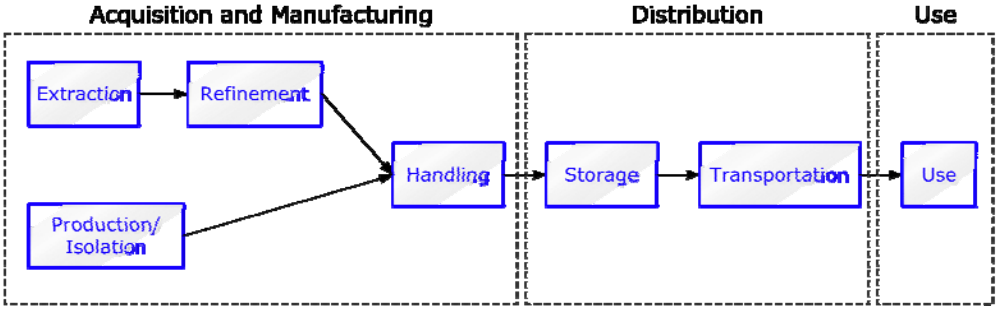

Figure 4: Rocket fuel life cycle

Using the LCA analysis method as a means of evaluating the true environmental impact of a fuel, the requirements established in Table 2 can be met. The following section will analyze the in- and output parameters that need to be identified and quantified for each of section of the life cycle. In general these parameters will include environmental discharge, materials and energy use.

LCA Applied to Acquisition and Manufacturing

There are two ways of acquiring and manufacturing fuel. The first; is to use the extraction and refinement process as is used when crude oil is to gasoline and the second; is to use a base set of chemicals and to actually chemically produce the fuel. Both require an influx of a base material and both consume energy thus having an environmental impact. Using kerosene and LH2 as examples of each of these processes the environmental in- and output will be discussed in terms of the acquisition and manufacturing of these fuels.

Kerosene is currently used in the Delta-II rocket produced by the United Launch Alliance in the United States. The specific highly refined kerosene used is known as RP-1. This kerosene is a C-12 molecule highly refined at 0.81g/ml. While it is possible to extract oil and refine it this would produce little fuel. A more practical and common approach is to begin the refinement of RP-1 of a higher quality already partially refined base stock. Kerosene rocket fuel must be very well refined to prevent the formation of soot, polymerization at high temperatures, and eventual engine damage. The major step in this process for petroleum fuels is thus the refinement (Wade, 2008). Figure 5 illustrates some of the factors to be considered in the acquisition and manufacturing.

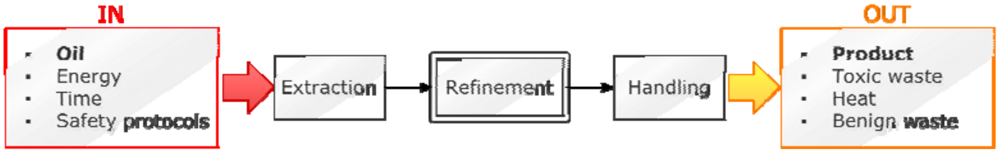

Figure 5: Fuel acquisition and manufacturing from oil

The second process of acquisition and manufacturing is via product isolation. This process distinguishes itself because it does not need to be extracted but rather it must be produced based on readily available materials. One example of this is LH2. LH2 is used in the Delta-IV and is a cryogenic fuel. Cryogenic fuel processes requires energy to refrigerate the fuel. Hydrogen, specifically, is difficult to contain because the molecules are very small and disburse quickly. In the model of small cryogenic molecules such as LH2, the handling plays a large role in the energy consumption. Figure 6 illustrates some of the factors to be considered in the acquisition and manufacturing.

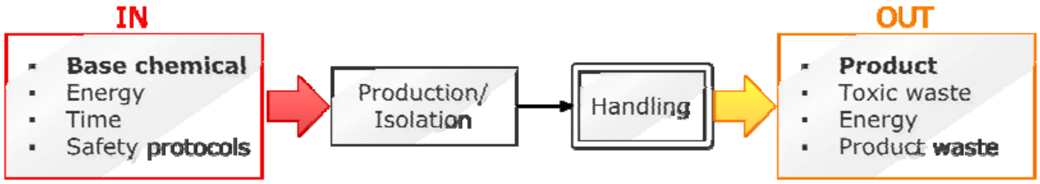

Figure 6: Acquisition and manufacturing of chemical based fuel

LCA Applied to Distribution

Different applications of rocket fuel have differing distribution requirements. Military applications require that the fuel is ready to be deployed quickly while commercial and civil applications tend not to need to store fuel. Depending on the use the requirements for this aspect of the life cycle needs to be weighted differently.

Distribution of fuel is made up of both transportation and storage. Ideally the acquisition and manufacturing would take place at the same location to limit the transportation environmental costs. Minimizing the amount of time in storage would decrease the environmental impact for 3 key reasons:

1. Decreasing the storage resources
2. Decreasing the necessity of fuel maintenance and monitoring
3. Minimizing wasted fuel

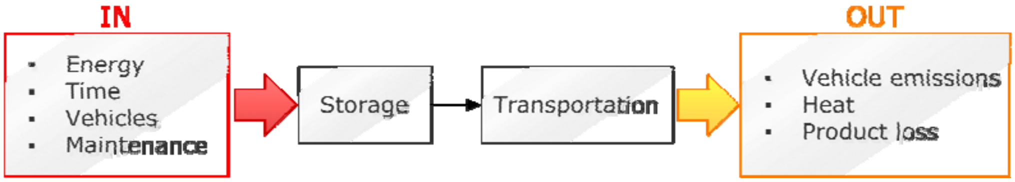

Figure 7: Fuel distribution

LCA Applied to Use

The use of rocket fuel is simply the burning of that fuel upon take-off. The chemical combustion produces thrust from the fuel exhaust being ejected out of the engines. Without the ejection of these particles, the rocket would not move and thus the size and speed of the exhaust are important to the physical rocket performance.

The location in the atmosphere where the exhaust is ejected plays an important role in the environmental significance. As discusses above, the effect that this environmental impact plays is almost always a temporary localized effect. The analysis of this aspect will need to take place for all levels of the atmosphere. Suggested in- and output parameters have been specified in Figure 8.

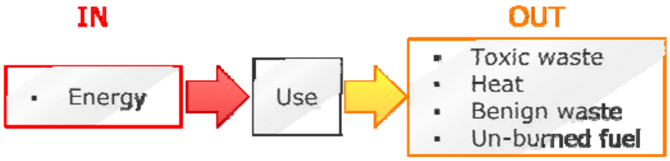

Figure 8: Fuel use

Application of LCA for Rocket Fuel

Once the LCA analysis of the entire fuel life cycle has been completed with all the in- and outputs, a narrow set of sustainable criteria must be established. As in the case of the automobile industry, it is unlikely that a single fuel will prove most efficient in every area of its life cycle. The set of sustainable criteria would need to be decided based on the primary environmental goals set out by each national space agency.

After an LCA is completed, assessment of the collected data would begin. The assessment could follow a structure similar to that outlined in Figure 9. The categorization would divide the resulting analysis data between: resources, consumption, and emission. The data would then be characterized and standardized it in a way that that would allow it to be compared and amalgamated. Impact indicators could then be used within a given category. The normalization step would make the data comparable to data outside the area of interest and is a means of putting the data into perspective. Finally, the impact indicators would need to be weighted placing priority on those areas or categories that are most relevant (EEO, 2002).

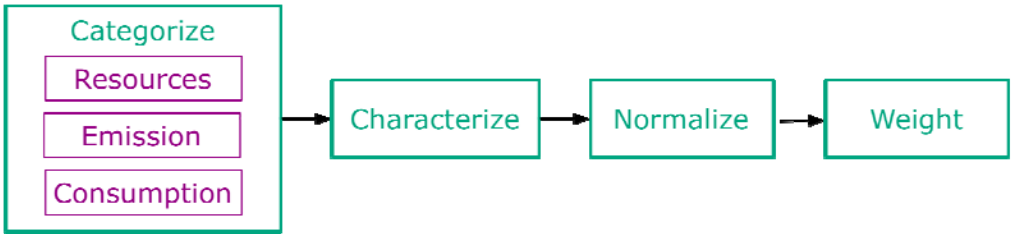

Figure 9: LCA Structure

Using the LCA the most significant manufacturing and handling environmental indicators could be determined for each fuel. This method does not assume that the ground environmental concern is always toxicity allowing for other factors, such as energy consumption, to be considered. Another strength of this method is its need for the national agency to have a clear understanding of their environmental goals. For space to truly be sustainable milestones are needed to track the progress and evaluation of these milestones can be accomplished through the LCA tool.

Using Green Engineering Principles in Rocket Fuel Development

A LCA is only the first step in green fuel development. Once rocket fuels can be assessed, fuel design can begin in a way to properly meet the requirements set out by the LCA. Green engineering principles were developed by Anastas (2003) to provide guidelines during the development of any product as a way of making environmental policies and mission statements attainable. It is the application of an environment focused life cycle design approach for both science and engineering. There are 12 principles that can be thought of as parameters and they can be found in Table 4. These parameters must be optimized as they are often not able to all be fully optimized. The life cycle sustainability approach requires that their be environmental objectives at all levels as well as at all design and manufacturing stages. From the molecular level to the product, process and system level, each must consider environmental implications.

Table 4: 12 Green engineering principles (Anastas, 2003)

Principle 1	Inherent design rather than circumstantial
Principle 2	Prevention instead of treatment
Principle 3	Design for separation
Principle 4	Maximize mass, energy, space and time efficiency
Principle 5	Out-pulled versus input-pushed
Principle 6	Conserve complexity
Principle 7	Durability rather than immortality
Principle 8	Meet need, minimize excess
Principle 9	Minimize material diversity
Principle 10	Integrate local material and energy flows
Principle 11	Design for commercial 'afterlife'
Principle 12	Renewable rather than depleting

This section will examine how these principles could be applied or have been applied in the past in the design of green rocket fuel. These principles can be applied to any stage of the fuel production to help decrease that aspect of the life cycle. It can also be applied to design completely new fuels. The principles marked in black in Table 4 will be further examined because of their particular relevance to fuel design.

Principle 1: Inherent design rather than circumstantial

Changing the fuel itself instead of mitigating the consequences through safety procedures is more sustainable and better for long-term environmental planning. Rocket fuel design is relatively new. Traditionally combustion has been a science of trial and error and not necessarily one of design, due to the complex nature of combustion chemistry. Rocket engines have been studied and changed to increase efficiency and now, as new materials become available new designs for both high and low thrust fuels are being considered.

One example of a low thrust rocket fuel is a nano-aluminum-water slurry. This combination has properties similar to a monopropellant with only non-toxic components. The use of nanotechnology in fuel development is a prime example of the advances in fuel design rather than circumstantial changes (Shafirovich, 2004).

Principle 2: Prevention instead of treatment

Currently the majority of the space industry takes more of a treatment approach when it comes to environmental pollution caused by fuel. This is because the fuel is selected for thrust and Isp rather than for environmental properties. There are multiple safety precautions and waste management programs attempt to for the use on non-sustainable fuel. As a consequence greater additional resources and investments for monitoring and control must be used (Anastas, 2003).

The Environmental Management Division (EMD) at NASA is charged with providing direct mission support by integrating environmental considerations into programs and projects (EMD, 2008). Within the EMD, NASA's Environmental Compliance and Restoration Program is mandated with clean up of the chemicals released into the environment due to past activities. (EMD 2008) These clean up programs are necessary but a paradigm shift to instead of treatment is needed for a sustainable fuel solution.

Principle 4: Maximize mass, energy, space and time efficiency

The design guideline to maximize the use of mass, energy, space and time efficiency is extremely applicable to space. For fuel design this guideline is more of a requirement and relates directly to performance criteria, such as Isp, and cost savings. Isp is by definition a measurement of fuel efficiency and it takes into account the mass required to achieve a given velocity. Time efficiency must be taken into account not only in fuel manufacturing but also throughout the life cycle. Currently the LH2 tanks of the space shuttle must first be purged of oxygen and then filled. This process is time consuming and inefficient.

The maximization of mass requires high-energy materials. These materials are currently being studied as replacement for solid rocket boosters. Examples of oxidizers being studied include Ammonium dinitramide (commonly referred to as ADN) and Hydrasinium nitrofomte (HNF) that have respective enthalpies of formation of -151 and -71 kJ/mole (Talawar, 2006). Chemical combustion relies on the decomposition of energy rich molecules and thus the lower energy of formation the greater the energy that is released upon decomposition. An ideal fuel being considered is cubane (C_8H_{18}) that upon oxidation releases 4643kJ/mole (Lo, 2001).

The problem with high energy density matter is stability and storage. Production of such chemicals is difficult and requires a lot of energy. The commonly used fuel, LH2, has extremely poor energy density but is used because of its high thrust capabilities. Optimization of multiple parameters must be considered and, as discussed previously, all of the parameters will not be optimized at once.

Principle 5: Out-pulled versus input-pushed

This concept is related to Le Châtelier's Principle on dynamic chemical equilibrium. The principle can be directly applied to fuel production because in most cases this is done using several chemical processes. In any chemical process equilibrium will be reached where the reaction forward will be equal to the reverse reaction. In this case the reaction must be pushed out of this equilibrium by adding more reactants, removing the product, or adding energy.

Often industrial cycles rely on the addition of energy to drive the reaction forward instead on product usage or the out-pulled effect (Anastas, 2003). By using the out-pulled action less energy would need to be spent. In a less strict sense approach could also serve as a 'just-in-time' approach meeting user end needs on schedule and in the exact quantity demanded.

Economically this principle poses a challenge because of the bulk = cheaper approach often taken in manufacturing. Within the space industry, where launchers are not made in traditional bulk numbers, this may pose less of a problem. Already, cryogenic fuels are being produced on the launch site to meet demands, thus decreasing the storage and transportation costs. One example of this is the NASA shuttle that is fueled on the launch pad.

Principle 8: Meet need, minimize excess

The nature of the space industry currently requires overdesign and redundancy because of the limited ability for service on orbit. Fuel margins are often high as the fuel is often what dictates end of life for satellites. Principle eight can still be applied to increase efficiency of fuel during use and to allow for the proper choice of fuel when optimizing between Isp and thrust.

Launcher stages, while inefficient in some ways, allow for the launch fuel to be used more efficiently. As the upper stages no longer have to provide lift to empty fuel tanks the fuel usage and be maximized to thrust to the payload. The use of stages also allow for flexibility in fuel choices because the most appropriate fuel can be selected at the most appropriate time. The environmental advantage in meeting the need instead of designing for excess is that fewer combustion products are released. This example deals not specifically with the design of the fuel but also the design of the launcher itself. Specifically, tri-propellant engines such as the kerosene, LH2, and LOX would be an example of using multiple stage rockets to use the fuel more effectively. The design of the whole system must be considered during fuel design.

There are other processes currently used that 'waste' fuel knowingly because of the fuel properties. The LH2 fueled into the external tanks before launch is expected to boil off before it is used and thus much of the produced fuel is wasted. Finding a way to improve this process could decrease the waste and increase the efficiency and thus minimize the environmental impact.

Principle 10: Integrate local material and energy flows

The production of fuel is only one aspect of launch vehicle production. The integration of materials and energy along all process could be used to increase the overall sustainability. Energy inputs from sources, such as heat from adjacent processes and the reuse of materials could decrease the need for additional energy and material inputs. The refrigeration cycle for the condensation of LH2 and LOX produces excess heat that could be used somewhere else in the process.

Principle 12: Renewable rather than depleting

The consideration of the renewable fuels has been discussed extensively in the automotive industry and is becoming a growing concern for the public. The fluctuating price of non-renewable sources, the limited resources that are available, and the environmental damage caused by the exhausts are some of the reasons for this concern. Renewability and long-term availability of rocket fuel must also be considered. As hydrocarbon molecules are being considered as alternatives to current fuel, the renewability of their source must also be considered.

Another renewable element to be considered is the energy source. Using renewable energy sources would set an example for other industries and make the industry look 'greener' from a public perspective. Because of the importance that public image has in the public space sector this element is important.

Challenges to Sustainable Fuel Development

Challenges and resistance to environmental solutions must also be considered when examining alternative fuel solutions. Recommendations made must take into account overall social goals, technological readiness, benefit balance, time constraints in developing new expertise and up front costs. For green fuel, the cost of developing new hardware, developing and maintaining new specialties, and the increased risk of failure due to lack of experience can cause changes to be slow. This section will outline the challenges of sustainable green fuel development and in particular the challenges faced by a life cycle approach in both assessment and design.

Social Challenges

Space technology has historically moved forward in a performance-first manner. The goals put forward by administrations are often to provide a technological push. One example of this is the development of space agencies in developing countries. The Indian Space Research Organization (ISRO), driven by the words of Dr. Vikram Sarabhai: "…we must be second to none in the application of advanced technologies to the real problems of man and society", represents an organization striving to develop application based space technologies. Their goals are inherently conflicted if these technologies harm the environment and this in-turn becomes one of the "real problems of man and society" (ISRO, 2009). The challenge for developing nations is primarily that the cost of entering the space industry is already high without considering new sustainable technologies. It is natural that the launch technologies used initially by developing space nations would be performance based.

Public space agencies are funded by public money and thus must demonstrate the results of their investments. While the world population is becoming increasingly aware of the importance of sustainable development, results are still important. The military space sector is more performance and result based and as more missions become 'dual-use' the requirements for sustainability become difficult to apply to public missions.

Technological Readiness

Proving technological readiness within the space industry is extremely difficult because of the difficulty in testing and the harsh space environment. Launch technology and fuel is critical to every mission and thus the introduction of new fuel will take years. The implementation of more sustainable fuels, like most new space technologies will be slow.

Haesler (2004) identified European development needs for hydrocarbon fuels with LOX as the oxidizer. The needs identified were primarily in increased research characteristics of fuels, engine coatings and materials. The focus of certain nations in particular areas of green fuel development stems from different levels of readiness in different countries. As the levels of expertise are not universal around the world, agencies have the tendency to develop technologies in their technological niches and to specialize.

Technological readiness also addresses the issue of chemical propulsion versus other launch technologies being investigated. A change in launch vehicle systems away from chemical propulsion seems far enough in the future that further investigations into improving chemical propulsion should continue, but if the goal is truly to develop the best system, this issue remains to be investigated in an environmental context.

Economic Challenges

There are also significant economic challenges in green fuel development. Costs are not simply for the development of a new fuel but the cost of performance testing, engine development and environmental testing. In a performance driven environment, such as the space industry, costs tend to be spent to improve performance unilaterally.

For this reason, solid propellants are expected to continue to plan a major role in the near future (2010 – 2020). This is due to the simplicity and reliability for expendable launch vehicles. Ammonium Nitrate (AN) has been proposed as a balance between environmental exhaust pollution, performance and cost (De Luca, 2004).

By modifying existing fuels, changing their production sites or changing manufacturing methods both the cost and environmental impact of a given fuel can decrease. The life cycle approach to obtain sustainability allows for small and gradual changes to be measured and accounted. As in most environmental solutions, sustainability does not need to develop in grandiose gestures but in small solutions.

Conclusion

The current status of the development of green rocket fuel is unclear with differing criteria and standards stretched across the globe. Environmental impact assessments are applied by national agencies on a voluntary basis and the assessments themselves differ leaving no way to compare between agencies. As sustainability becomes more socially, economically and environmentally important the use of life cycle analysis is becoming increasingly important.

The use of LCA for rocket fuel is concluded to be a good method for helping to analyze the current status of development within the space industry. An LCA analysis will also help to guide the design of environmental objectives at national agency level. Designing for sustainable rocket fuel can be done effectively by balancing the green engineering principles and considering the political, social and economic challenges specific to the space industry.

References

Accettura, Antonio G., *Advanced Propulsion Systems and Technologies Today to 2020*. Chapter 6 - Green Propellants, AIAA, pp.155- 180, 2008.

De Luca, L.T. et al., *Low-Cost and Green Solid Propellants for Space Propulsion.* Proc. 2nd Int. Conference on Green Propellants for Space Propulsion, June 2004.

Haeseler D. et al., *Green Propellant Propulsion Concepts for Space Transportation and Technology Development Needs.* Proc. 2nd Int. Conference on Green Propellants for Space Propulsion, June 2004.

Lo, Roger E. et al., *Green High Thrust Propulsion: Cryogenic Solid Propellants*. Proc. Int. Conference on Green Propellants for Space Propulsion, in combination with the 4th International Hydrogen Peroxide Propulsion Conference, June 2001.

Lo, Roger E. et al., *Advances in Green Cryogenic Solid Propellant Propulsion*. Proc. 2nd Int. Conference on Green Propellants for Space Propulsion, June 2004.

Shafirovich, Evgeny et al., *Nanoaluminium – Water Slurry: A novel "Green" Propellant for Space applications.* Proc. 2nd Int. Conference on Green Propellants for Space Propulsion, June 2004.

Talawar, M.B. et al., *Emerging Trends in Advanced High Energy Materials*. Combustion, Explosion and Shock Waves, Vol. 43, No. 1, pp. 62-72, 2007.

Urbansky, E. T., *Precholrate as an Environmental Contaminant.* Environ. Sci. & Pollut Res, Vol. 9 (3), pp. 187 – 192, 2002.

Valentian, Dominity et al., *Green Propellant Options for Launchers, Manned Capsules and Interplanetary Missions*. Proc. 2nd Int. Conference on Green Propellants for Space Propulsion, June 2004.

Wade, Mark, *LOX/ Kerosene*. Encyclopedia Astronautica, www.astronautix.com/props/loxosene.htm, Date of Access: 8/3/2009, 2008.

Energy Efficiency Office (EEO), *Life Cycle Assessment (LCA) and Life Cycle Costs (LCC) Tool*. and Mechanical Services Department, www.emsd.gov.hk/emsd/eng/pee/lceabc.shtml, Date of Access: 8/3/2009, Last Updated 12/2008, Document Created 2002

Environmental Management Division (EMD), *EMD Home*. NASA Headquarters, http://oim.hq.nasa.gov/oia/emd/index.html, Date of Access: 8/3/2009, Last Updated 02/2008

Anastas, Paul T and Julie B. Zimmerman, *Design through the 12 Principles of Green Engineering.* Environmental Science and Technology, American Chemical Society, March 2003

ISRO, *Indian Space Research Organization – About ISRO*. ISRO, Date of Access: 8/3/2009,