iNEMI Project on Alternative Materials Assessment

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Executive Summary

A framework for implementing alternatives assessment is necessary during product development of electrical and electronic equipment (EEE). There are many tools currently available to industry that can assist in the evaluation of alternatives and lead to more informed and better decisions with respect to the materials used to make products. However, no single tool can perform everything necessary to make the best decision and no single path through the framework will be right for all situations. The iNEMI project for Alternative Material Assessment has developed a suggested framework for Alternative Material evaluation. Additionally, the project team reviewed the assessment tools identified in the OECD Toolbox versus a set of benchmarking characteristics the team identified as necessary for conducting an alternative material assessment.

For the electronics and semiconductor industries, as well as for suppliers in the chemical industry where new, complex material development has a key role in advancing the next technology innovations, a proactive approach to addressing Environmental, Health and Safety (EHS) issues is a critical necessity, given lengthy development times. Moreover, new materials are often selected to meet very challenging technical requirements, and are processed in complex processing equipment where their specific integration is accomplished through extensive process development. Therefore, a belated discovery of any adverse EHS, sustainability, and product content issue has significant cost implications and thereby must be addressed up front. This situation is further complicated, by the rapidly evolving regulatory landscape, now trending toward a more precautionary approach for materials usage, and the vital business importance of protecting a company's intellectual property (IP).

Since the electronics industry is facing increasing attention to the materials used in EEE products both manufacturers and suppliers can benefit from evaluating the materials used in their products, especially when transitioning away from a chemical of concern. By employing the alternatives assessment framework presented herein, manufacturers can avoid moving from one chemical of concern to another and choose alternatives that will not become an issue in the future.

Additionally, the electronics industry would be well served to work towards standardization of alternatives assessments. The framework presented in this paper is based upon the National Academy of Science framework, considered to be the state-of-the-art in alternatives assessment [12]. When working with common suppliers and manufacturers it is helpful to speak the same language and setting the same requirements. Working toward standardized and abundant assessments of the important materials used in EEE will lead to better informed decisions earlier in the design process for both the manufacturer and the supplier.

Introduction

Background and motivations for alternatives assessments

Green Chemistry (GC) was introduced by Paul T. Anastas and John C. Warner in a 1998 book entitled *Green Chemistry, Theory & Practice*. In this comparatively short but seminal text, the authors highlighted 12 principles which exemplified the key concepts of GC, articulating the value of addressing Environmental Health and safety (EHS), sustainability and product content/ecology issues, beginning in the chemical design phase. While this approach of integrating EHS concerns early in the process is new, many aspects of GC emphasized in the book have been worked on for many years in our industries and others. This includes an emphasis on employing novel and more benign synthesis methods and precursors, the importance of Life Cycle thinking, long term implications and materials efficiency, natural resource conservation, employing more benign catalysts, substrates and reactants, less reaction steps, etc. Thereby, it serves to connect the technology of materials design and chemistry, with the broader implications of their properties in use, EHS affects and end-of-life challenges. It also represents a logical trend toward the upstream evaluation of such issues, and the acknowledgment that these challenges broadly cut across many sectors, with significant long term implications, requiring this sort of proactive approach, rather than the historic and more conventional procedure of reactively managing permits and regulations.

For the electronics and semiconductor industries, as well as for our suppliers in the chemical industry where new, complex material development has a key role in advancing the next technology innovations, a proactive approach to addressing EHS issues is a critical necessity, given lengthy development times. Moreover, new materials are often selected to meet very challenging technical requirements, and are processed in complex processing equipment where their specific integration is accomplished through extensive process development. Therefore, a belated discovery of any adverse EHS, sustainability, and product content issue has significant cost implications and thereby must be addressed up front. This situation is further complicated, by the rapidly evolving regulatory landscape, now trending toward a more precautionary approach toward materials usage, and the vital business importance of protecting a company's intellectual property (IP).

Beyond following the key 12 green chemistry principles laid out in the aforementioned text, which are particularly relevant to the materials (and equipment) design phase for future materials, there is also the greater challenge of addressing the impacts associated with existing materials in use today. The process of comprehensively evaluating and selecting more benign and less impactful materials is the objective for employing alternatives assessment (AA) strategies and in some ways can be thought of as the practical implementation vehicle of GC.

Given all the challenges and constraints described above, and general agreement amongst the project team members that there was no one approach or tool that was universally applicable or accepted for AA, this iNEMI sponsored project identified the following objectives for this initiative:

1. As an initial exercise, the team provided their respective inputs on what constituted an ‘ideal case’ for what an AA would look like.

2. Perform a broad and comprehensive ‘environmental scan’ on the current state of AA strategies, to form a foundation on which to build, for the project work.

3. Map out a hierarchical framework that lays out a common approach or path toward AA evaluation, which would serve the basis for standardization across multiple industries.

4. Choose several key materials of interest, that had industrial significance, were representative of materials usage challenges and would prove logical candidates, to use in the evaluation of alternatives assessment tools.

5. Develop an evaluation matrix, which included key AA tools of industry relevance (potential future regulatory agency use, technical value and capability), and a list of key descriptors and criteria that would be most effective in evaluating the important pros/cons of these respective tools.

6. Conduct a comparative review of each of the identified tools, in terms of their relative effectiveness under the specified criteria listed.

7. Make key recommendations and conclusions from the evaluation matrix results, which will serve as a reference document for the electronics and associated industries, and to provide a project team recommendation concerning whether a second phase of this project is required.

Through the project team work, several overarching themes became apparent and further made the case for the critical nature of establishing a flexible AA process . With the regular introduction of new materials, rapid pace of technology change, compelling technical need for materials that may not be benign, it became clear, of the importance of a common standardized approach and proactive engagement. Comprehending the unique nature of the electronics industry, therefore, requires a thoughtful translation of what GC and AA mean for our applications. Establishing a process of evaluation across the technology life cycle of the device, process or material is critical, given the necessity of using non-ideal materials, the relative cost/benefit trade-offs of a material, hazard versus risk, especially in the context of whether it is a process or product material, and the need to look at the overall risk assessment. Clearly a ‘green chemical’ has vastly different meaning and implications, depending on which industry or even specific use considered. However, the default approach to attain a completely benign material is a good initial goal, but by integrating assessment evaluations from the outset of the design process, or doing a comparison with an existing material (life cycle assessment [LCA]), we can at least ensure that we are driving toward a more 'sustainable' material, using a process that emphasizes ongoing continuous improvement. Materials need to be assessed not just for their intrinsic properties, but also in the context of the process tools and recipes in which they are used.

Another relevant element to this discussion, centers on how we define a 'green product'. Carrying over the same theme, a comprehensive LCA evaluation is crucial, so that the full view of a materials replacement can be understood in the broader perspective. For instance, choosing a material with a modest environmental impact for the end of life of a device that can be adequately addressed with an effective product take-back system should be deemed an overall preferred selection, if the long term effect of this choice, results in superior performance of the device during its operating lifetime. These are the types of criteria and tradeoffs that need to be evaluated proactively, to ensure that the best choice of material is made over the entire life cycle.

As described by the project objectives above, a key goal was for us to define collectively the most effective AA framework for the electronics (and associated) industry applications. By coalescing around a common starting point for AA evaluation, the team felt that this would drive consistency and enable standardization. At the next level down are particular AA methodologies such as LCAs, and below that an array of specific AA tools. Taking a methodical, decision tree approach to identifying what tool(s) are most appropriate for the particular questions and applications being used by a practitioner, thereby enables selection of the best tool.

The evaluation matrix for AA therefore, represents a broad comparative look at the relative strengths and weaknesses and applicability of the tools reviewed by the team, considering everything from their scope, ease of use, cost, degree of software platform sophistication and capability, and which entity created the tool. This last criterion is of significance, as highlighting who developed the tool, provides the context and implications of the tool's relevance and use. For instance, a tool created by an active regulatory government agency would have a different significance than one developed by a commercial entity, an NGO or by academia. Note that the makeup of our project team represented all these key perspectives by design, to ensure that the group took a broad view of the AA project.

Recent developments in alternatives assessment

When considering which AA tools to select for this evaluation, several key considerations were made. Given the array of tools available today and an ever-widening number of advances and applications emerging, a key initial concern was to focus on tools that were relevant to key regulatory government entities, such as Organisation for Economic Cooperation and Development (OECD) and the State of California, among others. The premise was that prioritizing these potentially important tools would provide valuable technical reference to both industry and government as well, in advance of their proliferation into the policy and regulatory space.

Additional alternatives assessment resources

As AA becomes a more commonly accepted technique, several organizations are developing resources that may prove useful to companies preparing to conduct an AA. Potential users should review these resources to determine if information is available to help with the proposed AA.

The US EPA DfE Program has conducted several AAs, which might be of interest to companies in the electronics industry. In addition and in conjunction with other EPA work, the Safer Choice Program has created a Safer Chemical Ingredient List (SCIL). SCIL identifies chemicals that have undergone a detailed CHA and found to meet the DfE criteria as a 'safer' chemical. DfE has grouped the chemicals by functional use. Electronics manufacturers looking for safer chemicals in specific applications may wish to review the SCIL to determine if any of these chemicals meet their needs. If so, the user has the satisfaction of understanding that the SCIL chemicals have undergone a detailed CHA and are unlikely to lead to a regrettable substation.

In addition to the DfE work, several organizations have collected both CHAs and example AAs which might prove informative to the new user. GreenScreens that have been conducted on specific chemicals may be found at three specific locations. Clean Production Action, the creator of the GreenScreen methodology, has developed a GreenScreen Store. The GreenScreen Store provides completed GreenScreen CHAs either for free or for purchase at a nominal cost. Chemicals available are also grouped by functional use. The IC2 has created the Chemical Hazard Assessment Database (CHAD) which makes available free GreenScreen and QCAT CHAs. The IC2 has also created the Alternatives Assessment Library which lists completed alternatives assessments and other useful documentation to help facilitate the AA process. Lastly for those users with access to the Pharos automated GreenScreen LT, Healthy Building Network, the creators of Pharos, have included a tab in their Chemical Materials database if a GreenScreen has previously been conducted on that specific chemical.

As the AA process becomes more widely adopted, these resources will continue to expand. For example, as the result of recent work, approximately 100 GreenScreen assessments have been added to the IC2 CHAD. The California SCP has initiated the AA process to meet their legislative requirements. Once begun, it is expected that additional example AAs will be made public available.

Application of Alternative Assessment in the Electronics Industry

As driven by the regulation, market incentive and social responsibility, the electronics industry is striving to identify, evaluate and select environmentally safer and more sustainable alternative chemicals and materials that are functionally and economically acceptable.

Regulation – In the last decade, there is an explosion of new environmental regulations across the world applicable to electronic products and manufacturing processes. These regulations have significantly reshaped the chemical and material selection in the electronics industry. One of the most impactful regulations is the European Union (EU) Restriction On the use of Hazardous Substances in electrical and electronic equipment directive, 2011/65/EU, also known as RoHS2.[1] RoHS2 restricts the use of lead, cadmium, mercury and hexavalent chromium (Cr (VI)) and two groups of brominated flame retardants, Polybrominated biphenyls (PBBs) and Polybrominated diphenyl ethers (PBDEs), in electrical and electronic products. In addition, four phthalates, Bis (2-ethylhexyl) phthalate (DEHP), Butyl benzyl phthalate (BBP), Dibutyl phthalate (DBP) and Diisobutyl phthalate (DIBP), will be restricted in the upcoming revision of the RoHS2.[2] The new restriction is expected to come into force in 2019. To ensure product compliance, a lot of activities are ongoing in the electronics industry to phase out these restricted substances and develop the alternatives. Currently, the material selection in the electronics industry is more focused on the functional performance, manufacturability, cost, etc., rather than the hazard and exposure as long as the materials under consideration do not contain any restricted substances. However, this will be changed as the chemical hazard assessment becomes a new regulatory requirement. For example, California Safer Consumer Products (SCP) Regulation requires the comparison between the chemical of concern and the alternatives with respect to the health and environmental hazards as well as the exposure pathways and life cycle impact.[3] Therefore, the regulations will be a major driver for the industry to develop an AA methodology and incorporate it into product development cycle.

Market incentive – Today's customers are more desiring for the green electronic products that are safer to human being and more sustainable to environment. Non-Government Organizations (NGOs) are pushing hard to urge the electronics industry to eliminate the hazardous substances not restricted by regulations. This poses a big challenge to the electronics industry but also creates a huge opportunity and market advantage for the companies that strive for innovation to bring green products to the market.

Social responsibility – Social responsibility is another important factor to drive the companies to go beyond the regulations and select safer chemicals and materials to enable the continual growth of their business and socio-economics. The leaders in electronics industry have incorporated the concept of chemical AA into the product development lifecycle as part of the continuous process improvement. For example, Hewlett Packard is using an AA tool to select alternatives in the material approval process.[4] Intel is planning to implement an enhanced green chemistry screening and selection process for 100% of new chemicals and gases by 2020.[5]

The material design and development in the electronics industry usually take several years and the cost to implement the change is significant. Therefore, it is important to compare the alternatives with the chemicals of concern based on their environmental profiles, functional performance and socio-economic behaviors to prevent any regrettable substitution being integrated into products. Currently there are many AA tools and methodologies available to assess the chemical hazard and exposure to human and the environment. However, none of them is specifically designed or suitable for the electronics industry due to the complexity of supply chain, sophisticated manufacturing process and various use condition of electronic products. Moreover, there is no unanimously accepted tool or methodology by governments and industries for AA to meet the regulatory requirement. This creates a big barrier for the electronics company to get a consistent and comparable assessment result and comply with regulations. Since most hazardous substances are used across many different electronic components and products, the elimination and substitution will impact the industry as a whole. Therefore, it is more efficient and cost effective for the electronic companies to jointly collaborate with governments, NGOs, academia and other industry associations to conduct AA for those substances of high concern, which can also give a stronger and more unified voice in conveying key messages. This Chapter summarizes some key AA projects driven by the collaboration.

United States Environmental Protection Agency (EPA) Design for the Environment (DfE) alternatives assessments

In the past decade, the electronics industry has been partnering with EPA DfE program to identify and assess the potential alternatives of several hazardous substances of high concern used in electronics products, such as brominated flame retardants and phthalate plasticizers, to help understand the human health and environmental impacts of these substances and their alternatives and drive materials selection decision making.

Alternative assessment of Tetrabromobisphenol-A (TBBPA) in printed circuit boards (PCB)[6]

TBBPA is a reactive flame retardant widely used in epoxy resin of PCB in electronics. This project started from 2006 and is aimed to provide the health and environmental data for the flame retardant alternatives to help the electronics industry with the decision-making in alterative materials selection. It mainly focuses on the comparison of human health and environmental attributes of TBBPA and 9 potential flame retardant alternatives. In addition, this project also incorporated life cycle thinking and explored the associated exposure pathways of these flame retardants. The draft report was first released in 2008 and updated in 2014.

Alternative assessment of Decabromodiphenyl Ether (DecaBDE)[7]

DecaBDE is one of the most common PBDEs used as flame retardant in plastics, textiles, construction materials. DecaBDE was historically found in many electronic products including cable, connector, plastic housing, etc., and has been phased out with the restriction of EU RoHS. This AA compared the human health and environmental hazard endpoints of DecaBDE with 29 potential alternatives in a variety of polymer materials. Some alternatives are predicted to be more environmentally preferable than DecaBDE based on the result, but the functional performance and socio-economic factors were not evaluated. This project kicked off in 2010 and the final report was published in 2014.

Alternative assessment of Hexabromocyclododecane (HBCD) [8]

HBCD is a brominated flame retardant found in plastic housing in electronic product and is classified as a Substance of Very High Concern (SVHC) under EU REACH (Registration, Evaluation, Authorization and Restriction of Chemicals). This project identified and assessed 3 viable alternatives of HBCD used in expanded polystyrene foam (EPS) and extruded polystyrene foam (XPS) and provided the relevant health and hazard information for decision making. This project was initiated in 2011 and completed in 2014.

Alternative assessment of certain phthalates [9]

Phthalates are used as plasticizer mainly in polyvinyl chloride (PVC) materials. EPA formed a partnership with NGOs, industry and academia in 2011 and intends to focus on health and environmental assessment of certain phthalates and their alternatives. Currently this project is on hold due to the Toxic Substances Control Act (TSCA) Work Plan on 6 phthalates which may include an AA similar to DfE project.

Green Chemistry & Commerce Council (GC3) alternative assessment of DEHP in wire and cable products[10]

In this pilot project, GC3 partnered with academia and electronics industry to identify and evaluate safer alternatives of DEHP as a plasticizer in wire and cable products. The goal is to establish a collaboration model to evaluate safer alternatives of hazardous substances to enable the decision-making in chemicals or materials selection. 9 alternative plasticizers, including 6 single-ingredient chemicals and 3 confidential commercial plasticizers with multiple ingredients, were evaluated with respective to human health and environmental hazards and provided with benchmark scores. Peer review was integrated as part of the verification process to ensure the results are transparent and objective. The assessment report was published in 2013.

BizNGO alternative assessment of DecaBDE in external computer housings[11]

According to California SCP regulation, the companies must conduct a two-stage alternative analysis and submit the preliminary and final reports if they have a product that is on the list of priority products and contains a candidate chemical. To evaluate the possibility of complying with this regulation within the legally required timeframe, BizNGO, an NGO consisting of a unique collaboration of businesses and environmental groups working together for safer chemicals & sustainable materials, kicked off a pilot study with electronics industry using DecaBDE (candidate chemical) in external computer housings (priority product) as an example. Since this study is aimed at the compliance process rather than the development of the technical content for DecaBDE alternatives assessment, the available hazard assessment data (e.g. EPA DfE flame retardant alternatives assessment) was used to simplify the process. Over 100 flame retardant alternatives were identified in the preliminary analysis, but most of them were screened out during the assessment process and only 20 are left in the second stage. This study shows that it is feasible to complete the assessment and submit the reports within the timeline for a well-studied substance by leveraging the existing hazard assessment result, but even so, it is still very challenging to fill the data gaps in some cases, especially for the socio-economic analysis. The data gap issues can be more dominant for some poorly-understood chemicals. The preliminary and final reports were released in 2014.

Chemical AA is still a new area to the electronics industry. The collaboration successfully demonstrates the concept and value of AAs in supporting decision making of material selection. It is expected that more electronic companies will integrate the AA into their material selection process and drive the supply chain for safer products.

Alternatives Assessment Framework

The iNEMI Alternatives Assessment Framework (iNEMI Framework, Figure 1) is based upon a framework published by the National Research Council (NRC) of the National Academy of Sciences (NRC Framework) [12]. The NRC Framework provides a step-by-step process to conduct an alternatives assessment; however, details on how to conduct the various steps may be found in additional resources used as the foundation of the NRC Framework including:

- US EPA DfE Chemical Alternatives Assessments [13].
- Interstate Chemicals Clearinghouse (IC2) Alternatives Assessment Guide [14].
- Toxic Use Research Institute (TURI) Alternatives Assessment Process Guidance [15].
- Lowell Center Alternatives Assessment Framework [16].
- REACH Guidance on the Preparation of An Application for Authorisation [17].
- BizNGO Alternatives Assessment Protocol [18].
- California SCP Regulation [19].
- German Guide on Sustainable Chemicals [20].
- United Nations Environmental Programme (UNEP) Persistent Organic Pollutants Review Committee General Guidance on Alternatives [21].

Each of the above documents has positives and negatives. Several, such as the DfE, IC2, TURI, etc., provide more specifics on how to assess important parameters such as hazard, exposure, performance, etc. Others provide concrete examples of how to conduct an alternatives assessment. The NRC Framework provides a summary of each document. The individual sources provide more detailed guidance in specific areas of interest.

The iNEMI Framework follows the general structure of the NRC Framework but has been streamlined to better meet the needs of electronics manufacturers. Several steps found in the NRC Framework have been eliminated from the INEMI Framework and the timing of certain evaluations has been changed. For example, both frameworks include exposure as a comparative evaluation. As stated in the NRC Framework, comparative exposure is not a traditional risk assessment but a relative and high level comparison of potential exposure differences between the chemical of concern and proposed alternatives. The INEMI Framework includes comparative exposure as an important component but includes it in the initial screening step as opposed to later in the process as identified in the NRC Framework. Both Frameworks, however, agree in principle and the slight deviations are unlikely to have any major impact upon the final selection of safer alternatives.

The INEMI Framework consists of five primary steps although all steps are not necessary in all alternatives assessments. Which steps are appropriate depend upon several of the assessment steps, the particular chemical, product or process under development and other factors such as the amount of expertise and resources available for the assessment. The 5 steps include:

Step 1: Identify Chemical of Concern

Step 2: Initial evaluation

Step 3: Initial Evaluation and Scoping

Step 4: Identify Potential Alternatives

Step 5: Assess alternatives

5a. Assess physiochemical properties

5b. Asses chemical hazards and identify relative hazards and data gaps

5c. Assess exposure potential of alternatives (optional)

5d. Consider life cycle issues (optional)

5e. Consider performance (optional)

5f. Consider cost and availability (optional)

5g. Consider social impacts (optional)

5h. Rank alternatives (if necessary)

5i. Identify alternatives (if necessary)

Each step will be explained in more detail in subsequent sections of this guide.

INEMI Framework:

Step 1: Identify Chemical of Concern

Prior to initiating an alternatives assessment, it is important to identify the chemical of concern (COC) which will be the focus of the assessment. For the purposes of this project, the COC selection is outside the scope of this framework. Selection of the COC is often driven by decisions made outside the alternatives assessment framework. Some typical causes for identification of a particular COC along with at least one example for each include:

- Bans or restrictions on specific COCs. State, local and federal governments may pass bans or restrictions on specific chemicals or class of chemicals. For example, many states banned certain flame retardants such as polybrominated diphenyl ethers.
- Regulatory requirements for an alternatives assessment for a specific chemical or chemical use. California's safer product initiative requiring an alternatives assessment on the use of methylene chloride in paint strippers.
- Consumer interest and demand. Consumers request for products free of specific COCs. For example, the recent interest in products that don't contain the chemical bis phenol A.
- Industry sustainability and/or corporate policy initiatives. Decisions to remove all halogenated flame retardants from electronic products.
- Regulatory avoidance: Decision to eliminate regrettable substitutions and make decisions to prevent possible future regulation of a COC for a set period of time (often 5-10 years).
- Corporate brand protection and market expansion: Interest in protecting brand and increasing market share by selling 'greener' products.

Other reasons for identifying a COC may exist. This Framework, however, assumes that the COC has been identified through an external process. The alternatives assessment process begins once the COC has been identified.

Step 2: Initial evaluation

This step gathers information pertinent to the COC for the alternatives assessment process. This includes chemical identify and function, impacts to health and the environment and potential exposure pathways. Basic information includes:

- Structure: The chemical structure is often important to how the chemical is used in the product or process under review. It also provides information for comparison with potential alternatives to identify those alternatives that may or may not meet the same functional need(s).
- Chemical Abstract Services number (CAS): A CAS is a unique identifier for a specific chemical or product. It enables the assessor to collect information specific to the chemical or product under review and prevents confusion between different chemicals or products. For example, many chemicals have a myriad of common names. A CAS identifies which of the common names is pertinent to the alternatives assessment process.
- Chemical use: How the chemical is used in the product? For example, does it function as a flame retardant? If so, viable alternatives must also fulfill this function. If the chemical does not fulfill any specific function, can it be eliminated without adversely affecting the end product? If this is true, it may be possible to avoid an alternatives assessment by simply eliminating the COC from the product without the need of finding a replacement.

- Human health and environmental impacts: What impacts does the COC have upon human health and the environment? Is it a carcinogen, an acute aquatic toxic, a PBT, etc.?
- Exposure pathways: What is its primary route of exposure? Does the COC create its major impact through the ingestion, dermal or oral route of exposure?

This information will help frame the alternatives assessment and define which parameters are most importance in identifying a potential safer alternative to a COC.

Step 3: Initial evaluation and Scoping

This step further scopes the alternatives assessment by deciding how the alternatives will be assessed, deciding how stakeholders will be involved and conducting an initial screen to remove any non-viable alternatives. The initial screen will help to concentrate limited resources upon the most viable alternatives. There are four primary objectives of this step:

3a. Determine appropriate level of stakeholder involvement. All alternatives assessments require input from stakeholders. Stakeholders may include suppliers, product formulators and manufacturers, corporate policy makers, marketers, customers, recyclers and those involved in end-of-life decisions, etc. In addition, stakeholder processes can span a large spectrum from limited involvement through solicitation of responses to specific questions to formation of a stakeholder committee involved in all decisions. Several source documents include information on stakeholder involvement that can help define this issue. For example, the IC2 Guide [14] contains a specific Stakeholder Module which might provide valuable guidance in this process. Documents such as DfE [12], BizNGO [16], TURI [15] and UNEP [21] among others also provide guidance on stakeholder involvement.

3b. Establish governing principles and constraints: In this step, the assessor determines what principles form the base of the alternatives assessment and the limitations being placed upon the assessment. Principles are typically broad and answer the question, what is a desirable outcome for this alternatives assessment? For example, DfE [13] established three principles for its alternatives assessment process. Alternatives must be 1) commercially available, 2) provide the same performance and 3) have less of a negative impact upon human health and the environment when compared with the COC.

Constraints address similar issues but focus the alternatives assessment on certain alternatives or eliminate undesirable alternatives. For example, Washington State in its assessment of alternatives to the flame retardant decabromodiphenyl ether [22] placed the constraint on the alternatives assessment that no halogenated alternatives could be considered. Persistence requirements in Washington State prevented the State from recommending a potential PBT as an alternative to an existing PBT. Similar decisions have occurred in the electronics industry when some manufacturers decided to eliminate PVC from all products. Other popular constraints include elimination of any alternative that increases the generation of hazardous waste, use of conflict minerals, limitations on cost, etc.

Both principles and constraints, however, help define the scope of the alternatives assessment and are an important step to consider before starting the alternatives assessment process.

3c. Determine relevant hazard criteria and potential exposure pathways: In this step, the assessor determines which hazard criteria will be selected for evaluation and comparison and evaluates which exposure pathways are the most relevant. A number of the tools provided in Chapter 4 define which hazard endpoints are used for comparison. For example, the GreenScreen for Safer Chemicals® (GreenScreen) [23] identifies 19 hazard endpoints and provides an algorithm which enables comparison between the COC and alternatives. The Quick Chemical Assessment Tool (QCAT) [24] reduces the number of GreenScreen hazard criteria to 9 priority endpoints. The assessor needs to identify and determine which hazard endpoints are most important for the particular chemical, product or process under review. To assist in this determination, the assessor should also evaluate potential routes of exposure and determine which routes have the greatest potential impact upon human health and the environment. If, for example, a chemical is applied directly to the skin, dermal sensitization and irritation/sensitization may be an important hazard endpoint. Any tool used should allow comparison between the COC and potential safer alternatives for any identified important hazard criteria.

3d. Plan assessment: Once the foundation has been established, the assessor must, using the information formulated in the previous steps, finalize the scope of the alternatives assessment. The assessor should decide which modules to use (see Step 5 for more information on the different modules) and, importantly, how to handle insufficient data. Insufficient data typically is represented by data gaps in the modules and/or assessment criteria and can make comparison between the COC and potential alternatives difficult. The assessor, however, should decide how the alternatives assessment will address data gaps. In some of the hazard assessment tools only specific data gaps are allowed. If an alternative lacks important data, the alternative is assumed to be unsuitable unless data is obtained. Other tools do not include an assessment of data gaps and often treat data gaps as inconsequential indicating that lack of negative data assume a chemical is safe. Decisions, however, on how to address data gaps can have an important impact on the results of any alternatives assessment and must be clearly stated in the formulation stage.

Step 4: Identify Potential Alternatives and conduct Initial Screen of Alternatives

Now that the alternatives assessment has been adequately scoped, potential alternatives may now be identified and screened. This process includes two major steps:

4a. Identify potential alternatives: A very broad evaluation of potential alternatives should include such variables as drop in replacement, product reformulation, product redesign which might eliminate the need for the COC, etc. For example, the State of Washington [22] in its evaluation of alternatives to the flame retardant decabromodiphenyl ether in upholstered furniture identified furniture redesign as the preferred alternative. Upholstered furniture could be and was being produced using fabric barriers that eliminated the need for chemical flame retardants. Given toxicity concerns associated with alternative flame retardants, chemical elimination became the preferred alternative. Similar decisions have also been made in the electronics industry where some manufacturers have identified chemical elimination as a highly preferred alternative and, in cases where no equivalent chemical alternative was found, often ended up as the preferred alternative.

4b. Conduct initial screen: As an alternatives assessment requires the dedication of extensive resources and can take an appreciable amount of time, it is often beneficial to conduct an initial screen of alternatives to focus limited resources and time on the most likely alternatives. Initial screens can be conducted on a number of factors such as hazard, performance, comparative exposure potential, etc. Based upon the identification of important hazard criteria and potential routes of exposure, it is often easy to remove less likely alternatives based upon a quick review of these factors. Tools have also been developed to assist in this process. For example, automated hazard tools based upon the GreenScreen List Translator (GreenScreen LT) allows a quick evaluation of authoritative sources for hazard concerns associated with known COCs. The assessor can quickly, easily and relatively inexpensively determine if any hazards are known about potential alternatives and if known whether they eliminate the potential alternative as favorable. Performance is also often used as a screening technique. Identifying whether or not an alternative performs the same function at an acceptable level can eliminate unfavorable alternatives. A third method recommended in the NRC report conducts a comparative exposure assessment. If, for example, a chemical is used in sufficiently large amounts to impact negatively human health and the environment, it may be removed as a viable alternative. Such exposure assessments are part of many existing alternatives assessments. The EPA DfE in its alternatives assessment process assumes that all alternatives possess an equivalent or lower exposure potential. Any that do not are removed from consideration. In this example, those alternatives selected for additional review pose an equivalent or lower potential exposure hazard. Exposure, therefore, does not play a prominent role in any further assessment of the potential alternatives.

If after completing this step no favorable alternatives remain, the INEMI model identifies the opportunity for research and product development (4c). In Step 4c, manufacturers are challenged to develop new alternatives that are safer, potentially using the GC principles [25].

If no alternatives remain, the alternatives assessment process is postponed until newer, safer alternatives are available. There are several instances in the iNEMI Framework where all safer alternatives have been eliminated, thereby providing the opportunity for innovation and product development. In those instances, the assessor documents the results of the assessment and includes all data and information justifying the elimination of all alternatives from further consideration. Transparency is a concept fundamental to the alternatives assessment process. Throughout the alternatives assessment, all decisions and data used must be clearly documented.

Step 5:

If potential safer alternatives remain, the alternatives assessment continues on to Step 5 where an in depth evaluation is made of all potential alternatives. Step 5 has five major areas of concern, i.e. assess physiochemical properties, conduct a chemical hazard assessment and compare alternatives with the COC, assess alternatives using additional, optional modules selected, rank alternatives and, lastly, implement alternatives and complete a final alternatives assessment report.

5a. <u>Assess physiochemical properties</u>: Physiochemical properties can often be used as an indicator of potential acceptability of an alternative. If, for example, an alternative was identified as highly flammable, it may be removed from consideration if the constraint was made by the assessor in the planning process to eliminate any potential chemicals that might increase the amount of hazardous waste generated. Many tools listed in the guidance provide examples of appropriate physiochemical properties that can be used in an alternatives assessment process. Physiochemical properties such as vapor pressure, octanol water coefficient, water solubility, etc. are often used to evaluate both potential routes of exposure and human health and environmental concerns. Caution should be taken when using physiochemical properties. Assumptions about how a chemical acts in the environment using physiochemical properties should never be used in lieu of scientific studies. For example, conclusions are often reached about transport in the environment based upon such physiochemical properties as water solubility. If a chemical, however, is found in scientific studies to have acted in a way that is not fully explained by the physiochemical properties, the assumptions should be based upon the scientific data. In addition, all relevant physiochemical properties must be considered when making an assumption about an alternative. For example, many highly hydrophobic flame retardants were identified as not being water soluble and volatile based upon physiochemical properties. This led to the assumption that these chemicals would not be transported far from a release point. Subsequent scientific studies identified that, although the physiochemical properties were correct, the assessors failed to include the fact that these hydrophobic particles regularly bind to small particles which are readily transported by water and air, thereby causing them to be found in even remote regions of the planet. As this example shows, physiochemical properties can provide a general picture but any assessment should be broad enough to consider all relevant factors and should depend upon pertinent scientific data where available.

5b. Chemical Hazard Assessment: In this step, an in depth chemical hazard assessment is conducted. There are numerous tools that can assist assessors in evaluating the impacts alternatives have upon human health and the environment. The EPA DfE Program, for example, provides guidance on the review of 17 hazard endpoints. The GreenScreen expands slightly upon this list and provides guidance on 19 potential hazard criteria while also providing an algorithm to separate out alternatives in four bins or 'benchmarks' ranging from chemicals of equal or greater hazard concerns (Benchmark 1) to preferred alternatives (Benchmark 4). How data gaps are handled also play an important role in this assessment. As in all steps of an alternatives assessment, this chemical hazard assessment must be document with a clear indication of data sources and values used and conclusions reach upon this data.

Once the chemical hazard assessments are complete, the assessor compares the alternatives against the COC and identifies those alternatives that do and do not have less impact upon human health and the environment. Those alternatives that appear 'safer' continue on for additional evaluation. Those that appear of equal or greater concern are removed from further consideration. As in other steps in this process, it is potentially possible that all of the alternatives are unfavorable. As shown in the iNEMI Framework, this decision must be documented and provides the opportunity for product innovation and research. If alternatives are found to be favorable, further evaluation occurs.

5c.-g. Additional Evaluation Parameters: These steps represent additional modules which the assessor may have decided to include in the alternatives assessment during the scoping phase. Many of the tools identified in the next section include recommendations on what additional criteria may be considered. For example, the IC2 Guide [14] recommends at a minimum the assessment of hazard, performance, cost & availability and exposure. Some of these modules may not be necessary if the initial screen indicated they would have no impact on the final decision as shown with the previous example of exposure. The California DTSC [19] is required by their legislation to include an evaluation of life cycle concerns (called Life Cycle Thinking in the California legislation); therefore any alternatives assessment done to meet California requirements should include an evaluation of life cycle concerns. One further factor to include in this section is the identification of how decisions will be made based upon the number of modules involved and the detailed the analysis. The IC2 Guide [14], for example, includes a Decision Module that provides some guidance on how decisions may be made.

Once the additional data has been created and an evaluation completed, the assessor is presented with the possibility that all potential alternatives were identified as unsatisfactory. It this is the case, the iNEMI module again directs the assessor to document the decisions made and the data used while identifying the need for product innovation and research. If some alternatives are still found to be favorable, the assessment continues.

Step 5h. Rank Alternatives: In this step, the assessor evaluates the remaining alternatives and ranks them from the most favorable to less favorable. Criteria for this ranking are decided by the assessor and may be factors not considered to this point. For example, an assessor may decide that a particular supplier is preferred because of a long-standing business relationship or that a particular alternative supports the company's sustainability goals better than another. Once chemicals have reached this point, however, they are all considered 'safer' alternatives to the COC. Which specific alternative is selected is left to the assessor. As in all steps in an alternatives assessment, however, an explanation should be included on what criteria and data were used for the ranking.

Step 5i. Implement Alternatives: The alternatives assessment process is complete. A 'safer' alternative has been identified, the process and data used to reach this conclusion is transparent and now needs to be implemented. The assessor should identify any constraints to replacement of the COC with the 'safer' alternative. For example, any changes to a manufacturing or procurement process take time; therefore, it would be appropriate to include a schedule for implementation and clearly identify when the replacement will be effected. Any other pertinent information or constraints to implementation should be noted here.

AA is complete! Based upon the iNEMI Framework, the AA is now complete. The subsequent sections provide more details on the specific tools.

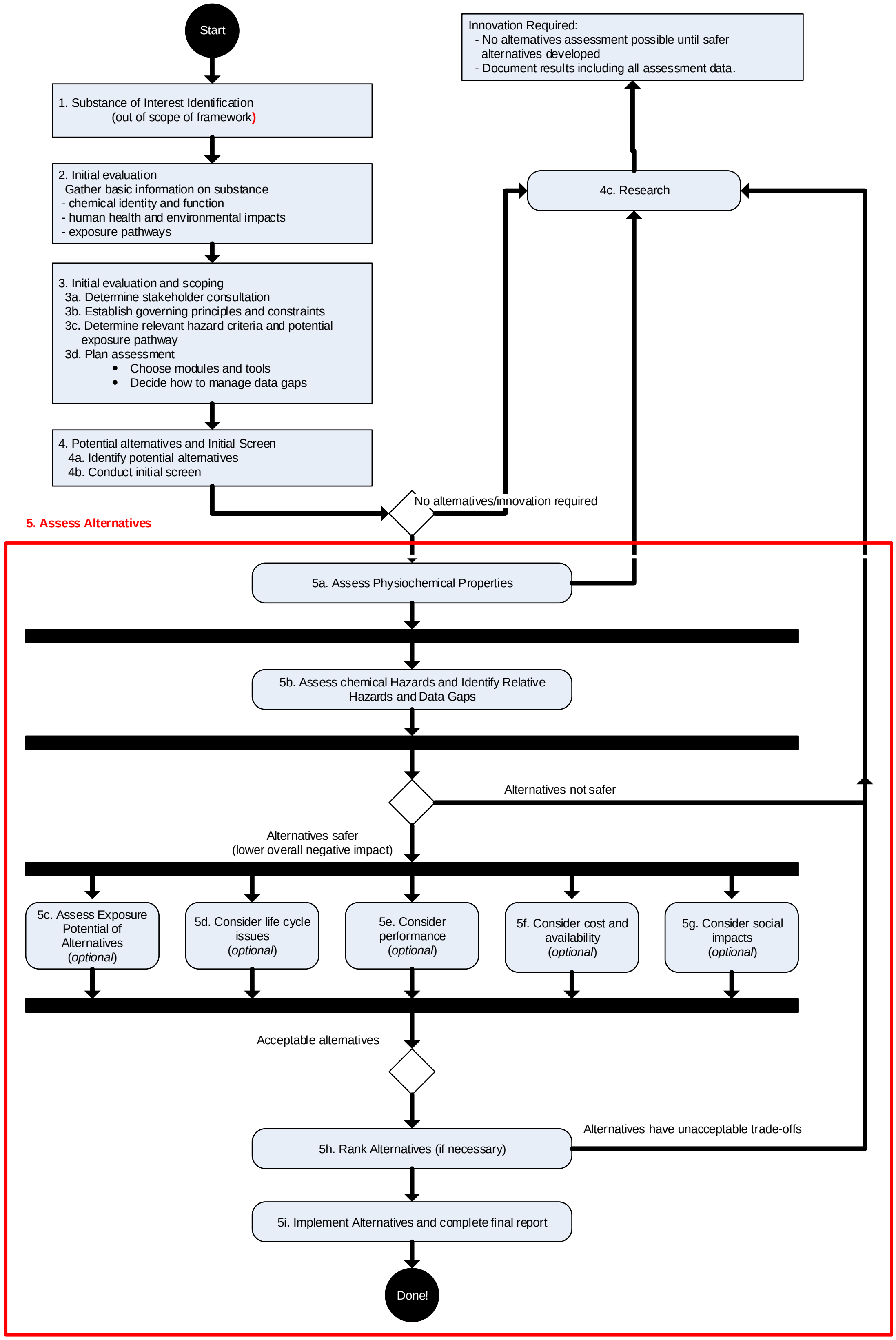

Figure 1: iNEMI Alternatives Assessment Framework

Alternatives assessment Tools

The team selected the following for evaluation as they were identified in the OECD Toolbox. For more details, see the AA Benchmarking tool spreadsheet.

Column Model

Column Model is a screening tool intended for a preliminary comparison between the substances or products and the alternatives for a quick decision making. The substances or products are evaluated by 6 columns of hazard categories which include acute health hazards, chronic health hazards, environmental hazards, physico-chemical hazards, hazards from released behavior and process related hazards. There are 5 risk levels for each column ranging from negligible to very high. The risk levels are determined by H phrases, physico-chemical properties and German hazard classes, etc., which can be found in the Material Safety Data Sheet (MSDS).

Green Chemistry Assistant

The Green Chemistry Assistant is a tool primarily geared toward students that allows them to do simple green chemistry calculations such as atom economy, percent excess, and theoretical yield; better organize "prelaboratory" work; generate Green Process Analysis Reports; and save your work or send the data and report to yourself or another person by email in a form that can be called up again at a later time.

The GreenScreen

The GreenScreen is a chemical hazard assessment (CHA) tool which is becoming the standard for comparing the hazard differences between a COC and potential alternatives. It is based upon the CHA process created by EPA's DfE Program and enables assessors to place alternatives into four bins or 'benchmarks'. Chemicals with equal or greater toxicity concerns compared to the COC are identified as chemicals to avoid (Benchmark 1) while alternatives with little negative impact are identified as preferred (Benchmark 4). Benchmarks 2 and 3 are chemicals to '*use but search for safer alternatives*' and '*use but still room for improvement*', respectively. The GreenScreen does require consider expertise and dedication of resources to complete a CHA as defined by the GreenScreen method; however, it does provide the most completed and detailed CHA available.

GreenScreen List Translator

The GreenScreen LT is a simplified CHA which determines whether or not alternatives have been identified as a chemical of concern by a number of approved authoritative sources. For example, authoritative sources such as the International Agency for Research on Cancer (IARC) [26], establishes several list of cancer inducing chemicals with varying degrees of carcinogenicity. The GreenScreen LT determines if any alternatives appear in these lists and, if so, if the degree of carcinogenicity is sufficient to cause concern. Those chemicals identified as a problem are assigned a ranking of LT-1 and should be removed as a viable alternative. The GreenScreen LT is very good at identifying chemicals that should be removed from consideration; however, chemicals not on these authoritative lists should not be assumed to be safe as they may not have yet undergone review. The GreenScreen LT has the added advantage that it has been automated (see Pharos below) enabling assessors to compare alternatives quickly and inexpensively against all authoritative lists used in the GreenScreen LT.

GreenWercs

GreenWercs is a service provided by The Wercs [26], a data provider primarily to industrial manufacturers and suppliers to major retailers such as Walmart, Target, etc. TheWercs provides assistance in green chemistry and sustainability solutions. This includes an automated authoritative list reviewer and a proprietary software package that attempts to use available data to lessen the negative impact products have upon human health and the environment.

iSUSTAIN (https://www.isustain.com/)

The iSUSTAIN Green Chemistry Index is a tool that uses the principles of green chemistry to generate a sustainability-based score for chemical products and processes. The tool requires the user to input a scenario that includes information about the process as well as the chemicals used in the product. A score is generated for each of the 12 principles of green chemistry and the results are displayed in a spider-graph format. The coefficients used to generate the scores are subjective and not transparent.

KEMI PRIO (http://www2.kemi.se/templates/PRIOEngframes____4144.aspx)

KEMI PRIO is a database of chemical assessments generated by the Swedish Chemical Agency. The database provides an authoritative source of information on the risk to human health and the environment. The database contains mostly hazardous substances with only limited instances of preferred alternatives.

Material IQ (http://www.materialiq.com/)

Material IQ is a service provide by GreenBlue [27], an environmental nonprofit dedicated to the sustainable use of materials in society. MaterialIQ is a tool that attempts to provide greater clarity on the chemicals and materials used in products. It provides validated CHAs, additional information on other concerns such as recycled content, CO2 emissions, carbon offsets, etc. and a graphical representation of the potential COCs in the manufacturer's products.

Oncologic™

OncoLogic™ is a desktop computer program that evaluates the likelihood that a chemical may cause cancer. OncoLogic™ has been peer reviewed, runs on a Windows® PC, and is being released by EPA at no cost, to be available to any researcher or organization wishing to evaluate cancer potential of chemicals.

P2OASYS

Pollution Prevention Options Assessment System (P2OASys) tool is developed by TURI for a comprehensive and systematic hazard evaluation of chemicals, processes and products. Before using the tool, users must populate the hazard data into a macro-enable Excel spreadsheet for the current technology and the alternatives under consideration. The tool uses embedded formula to automatically calculate the respective aggregated scores for comparison.

Paris III

The Program for Assisting the Replacement of Industrial Solvents (PARIS) III tool is a windows-based software tool developed by the US EPA to assist in solvent substitution and solvent design for reduced solvent environmental impact. The tool uses an internal database of chemical and physical properties as well as prediction routines to estimate values of solvent properties and thus create a solvent formulation to match user-defined tolerances. The tool key outputs are environmental impact scores for the original solvent formulation and ranking of alternative solvents with lower environmental impact.

Pharos

Pharos is a service provided by Healthy Building Network [28], a nonprofit created to reduce the use of hazardous chemicals in building products as a means of improving human health and the environment. Pharos is an automated version of the GreenScreen LT. It also functions as a repository for completed GreenScreen CHAs and includes other criteria of concern to building industry such as greenhouse gas content, life cycle research, etc.

QCAT

The Quick Chemical Assessment Tool (QCAT) is a simplified CHA tool created by the Washington State Department of Ecology [29]. QCAT is based upon the GreenScreen methodology but uses only 9 of the 18 hazard criteria found in GreenScreen. QCAT was designed for use by industry with less experience and expertise in the alternatives assessment field. The QCAT CHA is more complete than one conducted by the GreenScreen LT but less detailed than a full GreenScreen assessment. As with the GreenScreen LT, QCAT is most successful at identifying chemicals that are a poor alternative to the COC. It is not as effective at identifying safer alternatives but is a good introduction to both the CHA process and the alternatives assessment field.

Scivera Lens

Scivera Lens is a web-based CHA tool created by Scivera LLC [30], a for-profit consulting company *focused on delivering efficient, secure, and scalable technology solutions to our customers to enable scientifically-sound business decisions*. Scivera Lens is a proprietary tool which utilizes hazard assessment frameworks such as the GreenScreen. It includes an assessment using the GreenScreen LT and a second, more detailed assessment using a proprietary database of accumulated peer-reviewed scientific and toxicological data. The products of the Scivera Lens include a chemical risk assessment and a chemical hazard assessment similar to other CHAs identified in this Guide.

Choosing Tools to Make Informed Decisions

The tools presented in this paper offer valuable information individually but must be considered as part of a comprehensive analysis in order to make informed decisions. Some tools work well for certain types of substances and not others, and some tools work well for certain applications and not others. The analyst needs to choose the tools that fit the substance and application to provide the necessary data to make an informed decision.

It is important to guard against placing too much trust in the tool to provide the ultimate alternative. Some tools provide a summary for multiple endpoints that may not be sufficient if certain endpoints are more important than others. For instance, a substance may be found to be a GreenScreen benchmark 2 chemical but if it is going to be used in fish tanks the aquatic toxicity must be very low or it probably won't work for that application. In this case further investigation beyond the requirements for the GreenScreen might be necessary.

The tools have been grouped in the following tables in order to aid in tool selection.

Table 1. Comprehensive Hazard-Based Summary Tools

P2OASYS	61 criteria in 11 hazard categories
GreenScreen	18 Health and Environmental Endpoints

Table 2. Screening Tools for Preliminary Evaluation

Column Model	Kemiprio
GreenScreen List Translator	Paris III
GreenWERCS	QCAT

Isustain	Scivera Lens

Table 3. Tools by Assessor Skill Level

Novice	Moderate	Expert
GreenScreen List Translator	Column Model	GreenScreen
GreenWERCS	Paris III	Isustain
Kemiprio	QCAT	Oncologic
Scivera Lens		P2OASYS

Table 4. Tools by Expense

Free	Expense varies by chemical or requires annual subscription
Column Model	GreenScreen List Translator (Pharos - Automated Version)
GreenScreen	GreenWERCS
Isustain	Scivera Lens
Kemiprio	
Oncologic	
P2OASYS	
Paris III	
QCAT	
Green Screen List Translator (ChemHAT - Manual Version)	

Table 5. Tool Recommendation for Component Suppliers

GreenScreen
GreenScreen List Translator

QCAT
P2OASYS

Table 6. Tool Recommendations for Plastic/Polymer Suppliers

GreenScreen
GreenScreen List Translator
QCAT
P2OASYS

Limitations of Alternative Material Assessments

This paper has explored the potential benefits of various AA tools and includes a discussion of the application and selection of tools for evaluation. However, there are limits to the overall effectiveness of evaluating alternative materials in determining that one material is environmentally preferable to another. Such limitations can include the quality of inventory data, gaps in data, choices in methodology, and relative weighting of aspects. Therefore, an important aspect in conducting an alternative materials assessment is a comprehensive understanding of what is known and what is not known about the health and environmental impacts of the material under review.

Gaps in data should always be understood in the context of how they impact material handlers, end assessors and the environment. The alternative materials assessment should be conducted on a case-by-case basis in consideration of the anticipated application or use of the material. As such, any method used to 'score' alternative materials should be used in combination with other information including the health and environmental impacts of transformation products. This will help to avoid making material substitutions that may have only minimal, or even negative, overall impacts.

This paper has reviewed a series of tools to aid in the evaluation of alternative materials that may perform the same or similar function in applications specific to the electronics industry. The discussions herein have been further limited to health and environmental aspects and their impacts. No attempt has been made to evaluate other aspects that may be important to the selection of alternative materials, such as: cost of alternatives or energy and water consumption necessary to manufacture alternatives.

Understanding the benefits of alternative materials assessments and the inherent limitations to the process will help to inform decision making for alternative materials that demonstrate reduced health and environmental impacts. Alternative material assessment techniques should not be considered to be an end unto itself, but rather a tool to assist with decision making.

Conclusion

This paper provides a framework for implementing alternatives assessment in product development of electrical and electronic equipment (EEE). Within this framework there are many tools that can assist in the evaluation of alternatives and lead to more informed and better decisions with respect to the materials used to make products. No single tool can perform everything that is necessary to make the best decision and no single path through the framework will be right for all situations. The assessor must apply the framework and use the tools that provide data and answers that will help the product designers choose the material that is right for the application.

The electronics industry is facing increasing attention to the materials used in EEE products. Manufacturers and suppliers can benefit from evaluating the materials used in their products, especially when transitioning away from a chemical of concern. By employing the alternatives assessment framework presented in this paper, manufacturers can avoid moving from one chemical of concern to another and choose alternatives that will not become an issue in the future.

The electronics industry would be well served to work towards standardization of alternatives assessments. The framework presented in this paper is based on the work of the National Academy of Science framework, considered to be the state-of-the-art in alternatives assessment [12]. When working with common suppliers and manufacturers it is helpful to speak the same language. For instance, it is becoming common knowledge that a GreenScreen® benchmark 1 chemical is undesirable and may be subject to future regulation. Assessments for chemicals common to many manufacturers are already available, many for free, on various repositories. Working toward standardized and abundant assessments of the important materials used in EEE will lead to better informed decisions for all iNEMI members.

Appendix A: Acronyms and Abbreviations

AA	Alternatives Assessment
BBP	Butyl benzyl phthalate
BizNGO	An NGO consisting of a unique collaboration of businesses and environmental groups working together for safer chemicals & sustainable materials
CAS	Chemical Abstract Services number
CHA	Chemical hazard assessment
CHAD	Chemical Hazard Assessment Database
COC	Chemical of concern
Cr (VI)	hexavalent chromium
DBP	Dibutyl phthalate
DecaBDE	Decabromodiphenyl Ether
DEHP	Bis (2-ethylhexyl) phthalate
DfE	Design for the Environment Program
DIBP	Diisobutyl phthalate
DTSC	California Department of Toxic Substances Control
EHS	Environmental Health and Safety
EPA	United States Environmental Protection Agency
EPS	Expanded polystyrene foam
GC	Green Chemistry
GC3	Green Chemistry & Commerce Council
GreenScreen	GreenScreen for Safer Chemicals®
GreenScreen LT	GreenScreen List Translator
IARC	International Agency for Research on Cancer
IC2	Interstate Chemicals Clearinghouse
iNEMI	International Electronics Manufacturing Initiative
IP	Intellectual Property
LCA	Life Cycle Assessment
NGO	Non-Government Organization
NRC	National Research Council of the National Academy of Sciences
OECD	Organisation for Economic Cooperation and Development
P2OASys	Pollution Prevention Options Assessment System
PARIS	Program for Assisting the Replacement of Industrial Solvents
PBB	Polybrominated biphenyls
PBDE	Polybrominated diphenyl ethers
PBT	Persistent, Bioaccumulative and Toxic compound
PCB	Printed circuit boards
PVC	Polyvinyl chloride
QCAT	Quick Chemical Assessment Tool
REACH	Registration, Evaluation and Authorisation of CHemicals, Legislation in the EU
ROHS2	European Union (EU) Restriction On the use of Hazardous Substances in

	electrical and electronic equipment directive, 2011/65/EU
SCIL	Safer Chemical Ingredient
SCP	California Safer Consumer Products
SVHC	Substance of Very High Concern
SVHC	Substances of Very High Concern chemicals
TBBPA	Tetrabromobisphenol-A
TSCA	Toxic Substances Control Act
TURI	Toxic Use Research Institute
XPS	Extruded polystyrene foam

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