Validation of the Interagency Screening Tool for Critical Materials

Washington DC Project Center

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Abstract

The goal of this project was to validate the results of the Interagency Screening Tool created by the National Science and Technology Council Subcommittee on Critical and Strategic Mineral Supply Chains in order to improve its ability to detect for potential material criticality as tool helps to create policies that effect critical materials. We worked with the Office of Energy Policy and Systems Analysis in the Department of Energy to research historic cases of material market anomalies, that were compared the tool's results, and used to find new avenues for determining potential material criticality. The gathered data allowed suggestions for the methodology, interface, and scope of the tool to be created into order to improve performance and usability of the tool.

Authorship Page

Chris O’Shea, Drew Sansoucy, Rory Washburn, and Tung Truong all contributed to the project. The following is a detailed summary of who was responsible for each section. The introduction is made up of contributions by all members of the project. The section titled ‘Difficulties in Determining Criticality’ was written primarily by Rory Washburn and edited primarily by Chris O’Shea. Rory also was the primary author and editor of the section titled ‘Analysis of Tool Performance’ in addition to contributing to contributing to ‘Other improvements’. Chris O’Shea was the primary author of the ‘Future Analysis Possibilities’, ‘Historic Cases of Market Anomalies’ and ‘Project Goals’ sections with help from Drew Sansoucy and Tung Truong. Drew Sansoucy wrote the ‘NSTC and its Approach to Assessing Criticality’ section as well as ‘Other Improvements’ with help from Tung Truong. ’Making Recommendations for the Enhancements of the Tool’ in addition to ‘Tool Expansion’ and ‘Methodological Improvements’. The rest of the paper was completed with the help of all members of the team, with no primary author being discernible, so we feel it is not prudent to assign primary authors.

Executive Summary

Introduction & Background

As technological advances take place in society, the demand for raw materials with unique physical and chemical properties increases. Meeting this demand requires a dependable supply. However, markets for some materials periodically experience anomalies that can threaten supply reliability. Circumstances, such as these, can sometimes lead materials to be labeled as "critical". In 2010, fueled by concern over supply for critical raw materials, the National Science and Technology Council (NSTC) formed the Subcommittee for Critical and Strategic Mineral Supply Chains. In 2016, the Subcommittee developed the "Interagency Screening Tool (IST)" as part of an early warning system that enables government entities, industry, and other organizations to take action to prevent or mitigate the impacts of material criticality.

Criticality is a complex concept that means different things to different stakeholders. Thus, it is challenging to create a generalized approach which is effective for all the differing perspectives. In addition, there are many factors that impact criticality, such as demand growth, supply concentration, and substitutability. The problem with many of the factors involved in determining criticality is that they are not easily quantified. Even in cases where factors can be quantified, the data may be inaccessible or of questionable quality. The data is also often not reported on an ongoing basis - making regular assessment of criticality difficult. Because of these issues, the Subcommittee explicitly designed the tool to use publicly-available data that is updated annually to ensure that it can consistently calculate potential criticality.

Methodology

The goal of this project was to evaluate and improve the IST's ability to function as an early warning system by examining recent historical instances of material market anomalies and comparing them to the tool's results.

Our first objective was to find historic cases of material market anomalies to test against the tool. This list of material cases was created through research including analysis of news articles in business and trade publications along with information from the United States Geological Survey's Mineral Commodity Summaries, their special publications, and discussions with their commodity specialists.

Our second objective was to determine whether or not the tool captured the drivers behind each historical case of material market anomalies, and why. We explored methodological tweaks to demonstrate sensitivity of the tool to various assumptions as well as to relative weights of the indicators.

Our third objective was to create a set of recommendations for potential enhancements to the tool in order to enable it more effectively detect potential criticality, as well as expand the tool's scope and improve usability.

Findings

Our analysis of historic market anomalies consisted of going through all seven materials and gathered the drivers behind each material as well as the years of each anomaly. Table 1 shows a summary of drivers of the observed material market anomalies.

Material	Anomaly Years	Supply Chain Disruption[1]	Government Action[2]	Market Dynamics[3]	Tool Detection Years
Palladium	1999-2001			X	1996-2006
Tungsten	2004-Present	X	X		1999-2002, 2004-2009, 2011-2013
Tantalum	2000-2001			X	2000-2005
Tin	2007-2010	X	X	X	NA
Nickel	2006-2008			X	N/A
Tellurium	2008-2011			X	N/A
Rare Earths	2006-2013		X	X	2001-2003, 2005-2013

[1]Any sudden changes to a supply chain without warning, including natural disasters, strikes, and military conflicts
[2]Changes in government policy regarding material such as tariffs on imports and exports, mining subsidies, quotas on mining/production/exportation
[3]Changes in the market including global recession, speculation by investors, supply not/barely meeting demand due to a delayed response or lack of minable source

Table 1: Historic Cases of Material Market Anomalies

Overall, we found that the tool produced mixed results. With exceptions, the tool was quite able when predicting potential criticality for niche materials, but less so when looking more common materials. Looking at Table 1, the tool identified four of the seven tested materials as potentially critical, and of those four, three are fairly niche. Of the remaining three materials that were not detected, two are fairly common.

After researching each anomaly, we assessed how well the tool captured the drivers behind each case. While examining the performance of the tool in detecting each case, we noticed that the market dynamics (M) indicator tended to lag behind the others and suppress the overall criticality indicator even if the other two sub-indicators were rising. In other words, M indicator would not go above the 0.335 threshold until the actual year of the anomaly, while the supply risk (R) and production growth (I) indicators would reach the threshold ahead of the actual year where C reached the threshold.

We attempted multiple methods to improve the functionality of the tool. First we looked at how the potential criticality (C) value changed if we removed the M indicator entirely from the equation, which caused some material market anomalies to be detected earlier than previously. However, this new equation did not have the same effects across all materials. The next method was to weight the indicators differently using two different sets of weights, which focused on the weights of I and M while leaving R the same. These two equations would prove to be more effective in detecting the potential criticality earlier than just removing M from the equation entirely.

Another important methodological consideration underlying the tool is the default time period over which the M and I indicators are calculated. Varying the time period while looking at the effect on the potential criticality value demonstrated a clear sensitivity of the results to the assumed time period. Increasing the time window for both I and M to six years in comparison to the original five did allow for some of the materials to be marked as potentially critical earlier.

We combined the time window and weighting of the indicators into one equation which had the best results over the materials studied. This new equation predicted materials earlier as well as predicting materials that the tool had missed. Shown below in Table 2 is the summary of methodological analysis to the equation for calculating the potential criticality indicator.

Material	Original C	6 Year Period	C without M	Years Under Set1	Years Under Set2
Palladium	1999-2006	1998-2007	1996-1999, 2001-2007	1996-2008	1997-2006
Tungsten	1999-2002, 2004-2013	1999-2013	1996-2013	1998-2013	1998-2013
Tantalum	2000-2005	2000-2006	1998-1999	1998-2005	2000-2005
Tin		2007	2006-2007	1999-2007, 2013	2007
Nickel				2011-2013	
Tellurium				19961998, 2006, 2008	
Rare Earths	2006-2013	2001-2013	1996-2013	1996-2013	1996-2013

Table 2: Summary Table of Methodological Changes

Exercising the tool also revealed other areas for improvement that are not expressly methodological in nature, but nonetheless improve the usability and overall utility of the tool. For example, examination of materials that are precursors for other materials or that are linked via co-production or by-production was difficult with very few of these links expressly integrated into the tool’s user interface.

Recommendations

5.1: Methodological Improvements

We suggest a reevaluation of the default time period over which potential criticality is calculated given the sensitivity of the results. The default time period for the production growth (I) and market dynamics (M) indicators affects the results of the tool. We looked at many different time periods of 1 year through 10 years (the default being 5 years) and analyzed both the overall potential criticality (C) value and the individual indicators to see how changing the time period affects the tool's detection of potential criticality (C) value and individual indicators to see how changing the time period affects the tool detection of potential criticality. Overall, there is a clear sensitivity to the assumed time period. We found that a period of six years seemed to be most accurate in determining potential criticality.

We suggest considering assigning relative weights to the sub-indicators.

We found in many cases that the indicator for market dynamics (M) stays low until the anomaly occurs. The M indicator uses a measure of price volatility, but the price does not typically fluctuate until the anomaly has occurred, meaning that the tool can often will detect potential criticality later than the ideal time. We tried to correct this by changing the formula for C to weigh M less heavily and it showed positive results: detecting criticality earlier and in more cases.

5.2: Interface Improvements

We recommend that the colors for each country in the graph of production and price be standardized. Having a standard color for each color would make the tool easier to use.

We recommend that the colors for the indicators for the graph of single commodities time series and indicator tables are consistent for each material. The current color disparity causes problems in comparison between multiple materials, and fixing this would allow more effective usage of the tool.

5.3: Tool Expansion

We suggest that the tool be expanded to include links between materials. There are materials that are linked through co-production, or as by-products which can contribute to material criticality. In addition, the tool includes both materials and their precursors in some cases, such as aluminum and bauxite, respectively. However, the tool does not make this link apparent. Including this information can allow for easier and more in depth analysis to occur of these materials in the tool.

We suggest that the scope of the tool be expanded to include other materials such as isotopes, gases, and other chemical compounds. Information on these materials is widely available and many of these materials can be considered critical by their respective industry. The tool could cover these materials, and doing so would increase the tool usability.

We suggest that contract pricing be noted in the tool. In some cases, research indicated that much of the buying and selling of raw materials occurs via long-term contracts. It was not clear whether the price data in the tool takes this into account of only reports spot market prices. The tool would benefit from including contract pricing data which would allow analysis of certain materials to be easier**.**

5.4: Future Analysis Possibilities

Consider the usefulness of a ranked list comparing relative criticality values. The threshold value of 0.335 is arbitrary and does not reflect how criticality is a subjective concept. An idea we had come up with to fix this would be to report a chart that compared the potential criticality values, and even their sub indicators, creating a ranked list of the materials. These would remove the values from being the primary deliverable, which have the chance of easily confusing those who do not fully understand what they were looking at. The ranked list would also move focus to changes of ordering and the ordering year to year instead of the arbitrary value. More importantly, organizations and agencies could easily see how each material compared to others, which would make it easier to see which materials should have higher priority.

We suggest considering threshold values for the sub-indicators.

The threshold for criticality is not a definitive value and was determined based upon research by the Subcommittee. In some materials there is an indicator that is obviously approaching potential criticality, but not reflected by the overall C value. We suggest that there be some way to account for this, such as a threshold for indicators as well as overall criticality.

We suggest looking into the addition of more sub-indicators. Sub-indicators would be able to point towards more underlying causes of criticality such as substitutability. Including these would allow for an easier understanding of what caused the potential criticality of the material.

Conclusions

Overall we found the tool to be a very good indicator for potential criticality of niche materials based on the materials we studied. In most of the cases we examined, the tool detected potential criticality early and stayed above the threshold for the entire anomaly time period. Many of the cases where criticality was not detected were common metals such as tin or nickel. Adjustments to the tool’s methodology has the potential to increase the tool’s ability to detect potential criticality and enhancement to underlying data and the user interface can help improve the tool’s usability and overall utility.

Acknowledgements

We would like to thank our sponsors, Dr. Diana Bauer, PhD, and Fletcher Fields, who contributed a great deal to the development of this project and our report. By working with them we gained experience working in a professional environment, which will prove valuable in the future.

We would also like to thank our advisors, Prof. Stephen McCauley and Prof. James Hanlan, for assisting in the organization of this report and several presentations.

Table of Contents

List of Figures

List of Tables

1. Introduction

As technological advances take place in society, the demand for raw materials with unique physical and chemical properties increases. Meeting this demand requires a dependable supply. However, markets for some materials periodically experience anomalies that can threaten supply reliability. Circumstances such as these can sometimes lead materials to be labeled as “critical”.

There is no universally agreed upon definition for “critical minerals”, because it typically depends on the end-use application. However, the National Science and Technology Council (NSTC) recently defined “critical minerals” as “those that have a supply chain that is vulnerable to disruption, and that serve an essential function in the manufacture of a product, the absence of which would cause significant economic or security consequence” (NSTC 2016).

In 2010, fueled by concern over supply for critical raw materials, the National Science and Technology Council (NSTC) formed the Subcommittee for Critical and Strategic Mineral Supply Chains (the Subcommittee) under the Committee on Environment, Natural Resources, and Sustainability. The Subcommittee is responsible for working with member agencies to detect and signal “emerging critical or strategic materials” (CSMC, 2016). In 2016, the Subcommittee developed the “Interagency Screening Tool (IST)” to help identify materials with a high potential for criticality, economy wide. Using indicators derived from publicly-available, regularly-published data, the IST flags materials on an ongoing basis that may warrant further investigation into sources of criticality. The main objective of this tool is to provide an early warning system that enables government entities, industry, and other organizations to take action to prevent or mitigate the impacts of material criticality. For example, efforts can be made to secure supply from other sources or to find alternative materials.

The goal of this project was to evaluate and improve the IST’s ability to work as an early warning system by examining recent historical instances of material supply anomalies and comparing them to the tools results. After identifying cases where the tool would have failed to detect supply issues, we consulted with material experts and analyzed the tool’s underlying data in order to provide some recommendations for potential improvements.

2. Background

This chapter explains the many factors that can lead to a material becoming critical and the reasons the tool was developed. This is accomplished by exploring different materials and why different agencies might consider different materials critical. In addition, we introduce the National Science and Technology Council and their Interagency Screening Tool. We explore why the NSTC created this tool, the methodology used by it, and the tool's various uses. Finally, we explain our reasoning behind completing this research and how we conducted said research.

2.1 Difficulties in Determining Criticality

There is no agreed upon definition or way of determining criticality. This is rooted in the fact that each group concerned with supply of raw materials has different interests, and therefore has wide-ranging perspectives on what should be labeled as critical. Materials that are vital to one industry may have no uses at all in another industry. For example, The Department of Energy and the Department of Defense have different definitions for critical materials. The Department of Defense defines critical materials as materials that are used to "supply the military, industrial, and essential civilian needs of the United States during a national emergency and are not found or produced in the United States in sufficient quantities to meet such need" (DOD 2015). As shown in Figure 2, the Department of Energy's definition emphasizes the importance of the material to clean energy and the supply risk of the material (DOE 2011).

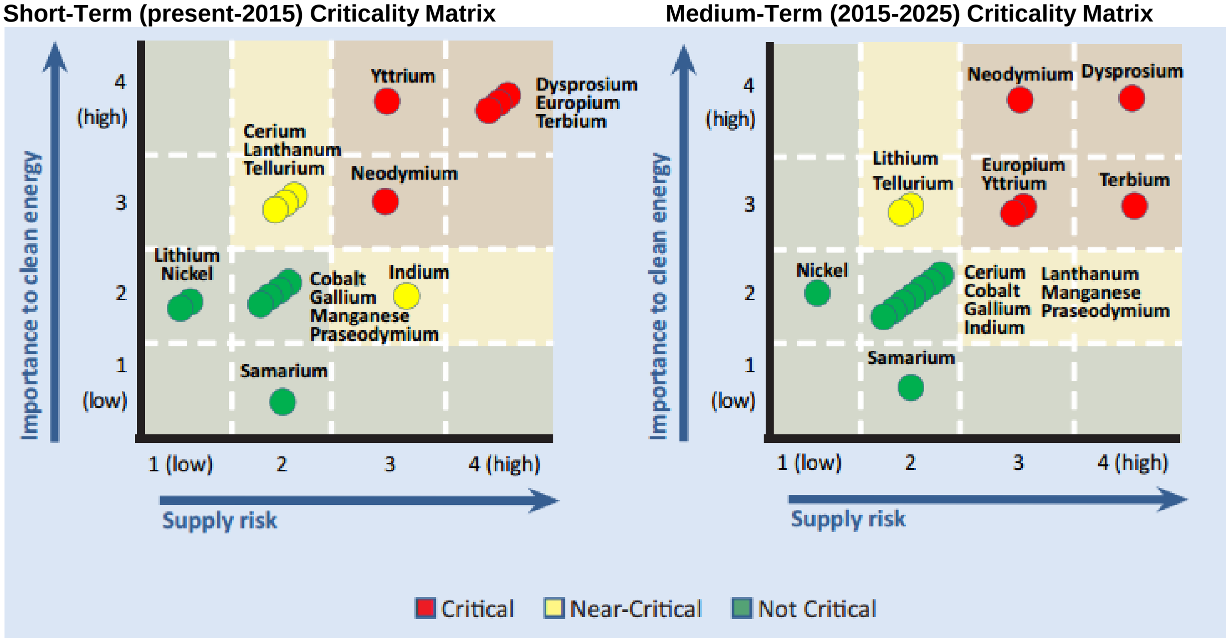


Figure 1: Short-term and medium-term criticality matrices for materials important to clean energy (DOE 2011)

Another dimension of complexity is the fact that there are a wide range of indicators that can be used to decide if a material is critical and most reports on material criticality consider different subsets of these factors, weighing each differently. In a 2015 report, the University of Augsburg identified 18 indicators that have appeared in one or more criticality studies from various countries, ranging from the United States to UK to Germany. Each of these studies also followed their own methodology, and examined different time periods. These factors fall under three different categories: Vulnerability, Supply Risk, and Environmental Risk(Figure 1).

Indicator	Dimension	Data type
• Geopolitical concentration	SR	●
• Static reserve range	SR	●
• Mine Production	SR	●
• Economic Relevance	VU	⊙
• Supply & demand trends	SR	●
• Strategic relevance	VU	⊙
• Recycling rates	SR	●
• Substitutability	VU / SR	⊙
• Production as by-product	SR	⊙
• Political conditions	VU	⊙
• Company concentration	SR	●
• Emerging technologies	VU / SR	⊙
• Production costs	SR	●
• Functionality & Technology	VU	⊙
• Ability to drive through price incr.	VU	⊙
• Damage Potential	ER	●
• Impact on climate change	SR / ER	⊙
• Exploration budget & investment	SR	●

Frequency of criteria in criticality studies

⊙: Qualitative data ●: Quantitative data VU: Vulnerabilty SR: Supply risk ER: Environmental risk

Figure 2: The Scope of Factors for Criticality Used in Various Criticality Studies, as Compiled by the Institute for Materials Resource Management, a subset of the University of Augsburg, in Augsburg, Germany (Mayer and Gleich 2015)

For the most part, factors that fall under the Vulnerability category, in Figure 1 are the demand-side indicators of criticality. Many of them involve the material's importance to various bodies, such as economies (Economic Relevance), militaries (Strategic Relevance), or technology (Emerging Technologies and Functionality & Technology). An important fact to note is that every factor that falls into this category also falls into the category of qualitative, so they don't have values that can be directly reported, but must be explained with words, or else inferred using values that can be produced for related systems.

Supply Risk refers to factors that fall more directly relate to a material's supply chain, and not the bodies that are the endpoints of said supply chains. These factors include where the material is concentrated in the world (Geopolitical Concentration), the budget allotted to explore new uses of the material (Exploration Budget & Investment), and whether or not the material is a byproduct of another material's production (Production as Byproduct). Also, as all of the factors under Vulnerability were qualitative, almost all of the factors under Supply Risk are quantitative. The exceptions are those factors which are split between two factors, and Production as Byproduct, which is primarily a yes or no question.

Environmental Risk is the easiest to describe, but the most difficult to see trends with. Simply put, it is the risk that the material and/or its supply chain will have a damaging effect on the environment. There are only two factors within this category: how much damage a material can have on the environment (Damage Potential) and how the material would affect climate change (Impact on Climate Change) (Mayer and Gleich 2015).

2.2 NSTC and Its Approach to Assessing Criticality

The NSTC was created by Executive Order on November 23, 1993 as a means to coordinate technology and science policy across Federal research and development enterprises. Its primary objective is to establish clear national goals for Federal science and technology investments (NSTC 2016).

The Subcommittee on Critical and Strategic Mineral Supply Chains was created in 2010 by action of the NSTC Committee on Environment, Natural Resources, and Sustainability (CENRS). The purpose of the Subcommittee is to "facilitate a strong, coordinated effort across Federal agencies to identify and address important implications arising from critical and strategic mineral supply issues" (CSMSC Charter Art C, 2016). The Subcommittee works with the CSMSC member agencies to assesses mineral criticality and mark emerging critical or strategic minerals. Another function of the Subcommittee is to assess domestic and global policies on critical and strategic minerals on the U.S. and analyze strategies for risk mitigation (CSMSC Charter Art C, 2016). The Subcommittee also has a function to identify cross-agency opportunities in critical and strategic minerals and to coordinate research and development for alternatives to critical and strategic minerals (CSMSC Charter Art C, 2016).

In order to assess criticality, the Subcommittee developed a two-phase approach. The first phase consists of the Interagency Screening Tool (IST), which attempts to identify potentially critical materials through early warning screening. The IST systematically analyzes an expansive list of raw materials using indicators related to the material's supply risk, production growth, and market dynamics. The IST uses these indicators as they are qualitative and easier to track.

In the words of the NSTC, "The supply risk indicator aims to assess the relative risk of a supply disruption by quantifying the geopolitical concentration of a mineral's production" (NTSC 2016). Simply put, supply risk measures the amount of uncertainty in a supply chain based upon the concentration of mining activity in a country, weighted by the instability of that country. This is done using two specific values: The Herfindahl-Hirschman Index (HHI) and the Worldwide Governance Indicators (WGI) from the World Bank. The HHI typically is a measure that relates the number of firms within a market to the size of said firms in relation to the total market (US Department of Justice 2015), but in this case it is applied on a country-level instead of a company-level. The WGI is a bit more complicated. The WGI are a group of six indicators that each say something different about a government. These indicators are 1) Voice and Accountability, 2) Political Stability and Absence of Violence, 3) Government Effectiveness, 4) Regulatory Quality, 5) Rule of Law, and 6) Control of Corruption. However, the indicator used in calculating supply risk is a composite of all six (NSTC 2016). For a more detailed description of the WGI see Appendix A. The point of these indicators is to provide a quantitative and unbiased method of analyzing the stability of countries which supply these materials. An unbiased opinion is formed by "30 individual data sources produced by a variety of survey institutes, think tanks, non-governmental organizations, international organizations, and private sector firms” (Kaufmann D. et al. 2010).

The production growth indicator aims to “capture trends related to a mineral’s market size by quantifying recent changes in its global primary production” (NSTC 2016). This indicator was calculated by looking at the primary production of the material, provided by the USGS, over consecutive years using a variable time which defaults to five years. The production growth indicator is important because the growth of a materials production often hints at an increase in demand on the global scale.

As the market dynamics indicator is currently, “The market dynamics indicator aims to capture the robustness of the mineral to sudden market changes by quantifying its price volatility” (NSTC 2016). In short, it is an indicator of how easily a material’s market is able to react and recover to sudden and potentially drastic changes in the global market.

The Subcommittee intentionally kept the methodology simple and straightforward so it could be transparent and repeatable. The Subcommittee also intentionally designed the tool to only rely on publicly-available data that is published regularly and on an ongoing basis. This allows the results from the tool to be easily updated.

It is important to note that this tool does not determine criticality as a final decision; rather, it lets the user know which material is possibly at risk and alerts them to do a more in-depth analysis of said material (phase two). When the tool’s criticality value goes above the “critical threshold,” this does not automatically mean that the material is critical, it just signals that it should be looked at more closely. The IST is the first step in determining the criticality of a material. If a material has been identified as potentially critical by the IST, it moves along to the second stage of the process, which is an in depth analysis of the material (NSTC, 2016). The goal of the in-depth analysis is to use reports and market trends to assess the impacts that a loss of a critical material would have on our economy and security as well as focusing on specific materials for further analysis and research (NSTC 2016).

2.3 Project Goals

As co-chair of the Subcommittee, the Department of Energy is interested in exploring ways to enhance the IST to more effectively flag potential criticality.

Our goal was to validate the results of the IST as well as recommend potential enhancements to the tool. This goal was accomplished by examining how well the IST detected historic cases of material market anomalies. The results of this examination were used to validate the methodology of the tool as well and to identify ways the tool could be improved to capture the dynamics relevant to these cases.

3. Methodology

The goal of the project was to validate the IST and to develop recommendations for improvements. This section includes descriptions of the research methods used to reach this goal:

- Identify the drivers of historic cases of material market anomalies
- Examine why the tool did or did not detect these drivers
- Make recommendations for enhancements to the tool

3.1 Identify the Drivers of Historic Cases of Material Market Anomalies

Our first objective was to determine cases of material market anomalies that impacted the reliability of supply for that material. In identifying these cases, we did not use the tool's results or underlying data in order to avoid potential bias. First, we created a preliminary list of materials, the markets of which have experienced anomalies of various types in the last twenty years. The preliminary list was created by looking through multiple news articles that discuss anomalies. These anomalies range from supply chain disruptions and price spikes to government legislation blocking the trade of certain goods. After documenti what kind of anomaly occurred, the primary reasons for the anomaly, and the time period over which the anomaly occurred, this information was corroborated through research into the USGS mineral commodity summaries and special publications over the last 20 years.

Different types of materials and different anomalies were sought out in order to effectively test the tool. The increased variety allows multiple facets of the tool to be tested and analyzed for any shortcomings and strengths. The variety of materials and anomalies also reflects the complexity of the real world which the tool needs to be able to analyze.

The initial list was then cut down to seven potential materials by removing any material not in the IST. Each material needed to be in the tool in order to be used to validate the results of the tool. For the materials not in the tool, another list was created to show how the scope of the tool could be expanded. For example, molybdenum-99m was not in the tool, but it is very important for the medical industry and shows historic cases of market anomalies.

The second half of the first objective was to expand upon researched knowledge of the materials that were chosen to test the tool. The expansion of knowledge was done in order to gain a deeper understanding of why these materials had an anomaly. Further research on each material allows for more insights behind the anomalies which in turn allows for greater analysis of the tool. The research might bring up underlying information that was not present in the mineral commodities summaries or the news articles. The information also allowed for stronger cases for each material in the final presentation.

An important aspect of this phase was to talk with experts in each of the identified materials. Therefore, several discussions with USGS mineral commodities specialists were set up. These discussions provided deeper insight into the historical market dynamics of each material in these interviews.

3.2 Examine Why the Tool Did or Did Not Detect These Drivers

The application of the tool to each material was used to determine whether it detected each case of material market anomalies. When tool was applied to each material, the material was identified as being potentially critical or not over the full spread of available data from 1996 to 2013. If the tool succeeded in identifying a material as potentially critical, then the material data from the tool was analyzed to see how it relates to the information we collected during the first step of the methodology. In the other case, where the tool failed to detect the historic market anomaly, the tool’s data was analyzed further in order to make recommendations for enhancements.

3.3 Making Recommendations for Enhancements to the Tool

In the final objective, a set of recommendations for the IST and the NSTC were created. These recommendations were created to improve the tool's ability to act as an early-warning screening tool. In addition, recommendations regarding expansion of the tool and interface improvements were made in order to increase its usefulness. These recommendations were presented with findings and analyses to our sponsors and members of the NSTC Subcommittee. The written recommendations along with the report were also shared with our sponsors and the NSTC Subcommittee.

4. Findings

Through the news article search over the last 25 years, we created a list of historical anomalies. Our original list consisted of tellurium, helium, rubber, nylon, silicon, plutonium, aluminum, iron, rosin, acrylic acid, carbon black, titanium dioxide, nitrocellulose, lithium, cement, sawdust, steel, iron, molybdenum-99m, bauxite/aluminum, manganese, and indium tin oxide. The list was eventually narrowed to seven materials, with rare earths as a comparison: tellurium, tantalum, tungsten, tin, nickel, and palladium, based on USGS yearbooks, USGS Mineral Commodity Summaries, and factors that we find from our further research on the materials.

Indium tin oxide, sawdust, cement, nitrocellulose, rosin, acrylic acid, carbon black, titanium dioxide, plutonium, rubber, molybdenum-99m, and nylon did not have data in the tool, and were not studied. However, this provides a list of materials the tool could be expanded to include if additional data became available.

Each of the seven materials on the final list were further analyzed to determine the drivers behind their historic cases of market anomalies

4.1 Historic Cases of Material Market Anomalies

Palladium

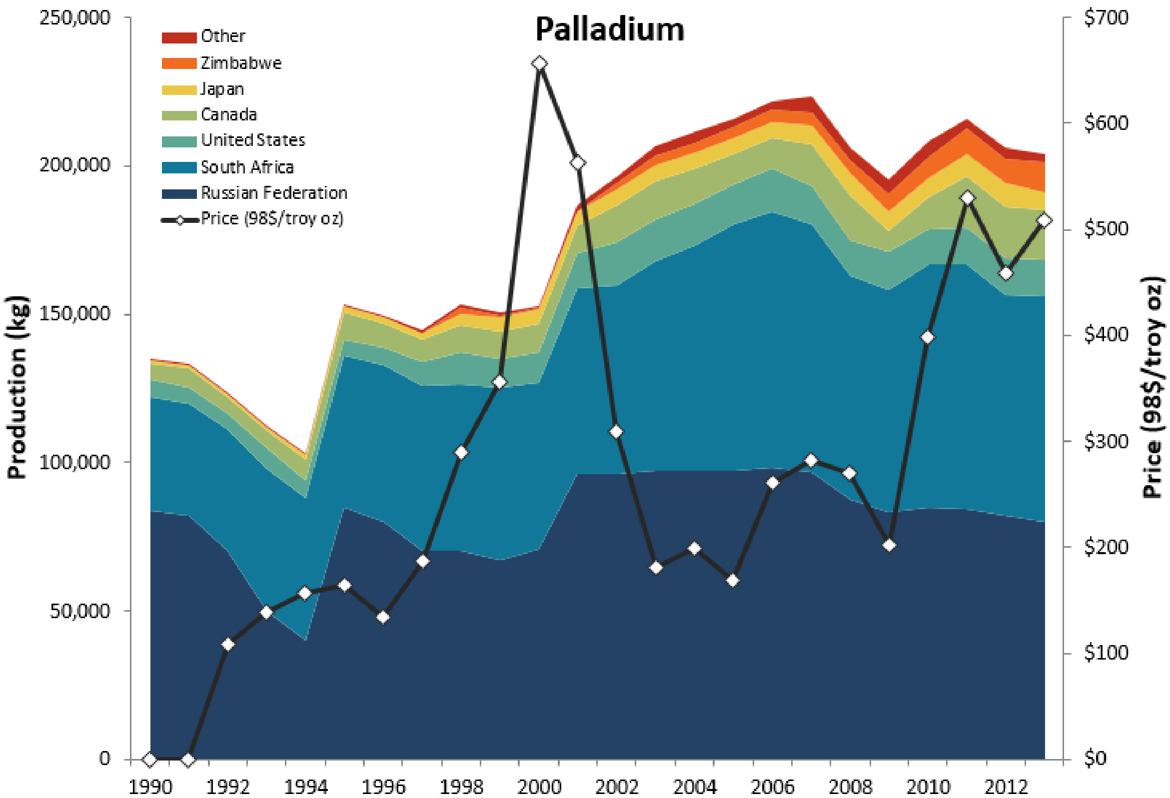


Figure 3: Price and Production of Palladium from 1990 to 2013 (NSTC 2016)

Palladium, illustrated above in Figure 3, is a platinum group metal (PGM) primarily used in the production of catalytic converters which allow toxic byproducts from the combustion of hydrocarbons to be broken down into less harmful compounds. Palladium's only effective substitutes are the other PGMs which react in very similar ways, but are generally more expensive.

In 2001, the price of palladium spiked due to an increased demand from the automobile industry as well as a supply chain disruption from the primary supplier, Russia (USGS 2010). During this time, 73% of the global demand for palladium was accounted for by the automobile industry according to Johnson Matthey, specialty chemicals maker (Shumsky 2014). In the years immediately before 2001, the US placed more stringent limits on the amount of hydrocarbons automobiles can emit, leading to an increased use of palladium for catalytic converters to reduce automobile emissions. Over the course of 2000, palladium prices rose drastically due to worries that the escalating conflict between Russia and the Ukraine would prompt supply disruptions. Since Russia accounted for over 40% of the world's supply of palladium at the time, the possibility of a disruption was viewed as a global disaster (Shumsky 2014). As Russian stockpile and production data for PGMs are a state secret, there was much uncertainty as to the Russian supply during this time. The data available on this stockpile are inferences and estimations based upon information such as Russian exportation numbers.

After palladium's peak in 2001, its high price led automobile manufacturers to substitute palladium for currently cheaper PGMs such as platinum and rhodium, decreasing demand for palladium, returning pricing to their original levels (USGS 2010). The high price of palladium also lead to research into non PGMs that could be used in catalytic converters such as copper and nickel. Shown in Figure 4, is the prices of the PGMs from 1993-2008. Ultimately, the research concluded that there were no substitutes nearly as effective as the PGMs in the field of hydrocarbon emission reduction (USGS 2002). As prices decreased in 2003 due to an excess in supply as well as liquidation of palladium stocks by investors, automakers switched back to palladium for catalytic converters (USGS 2004).

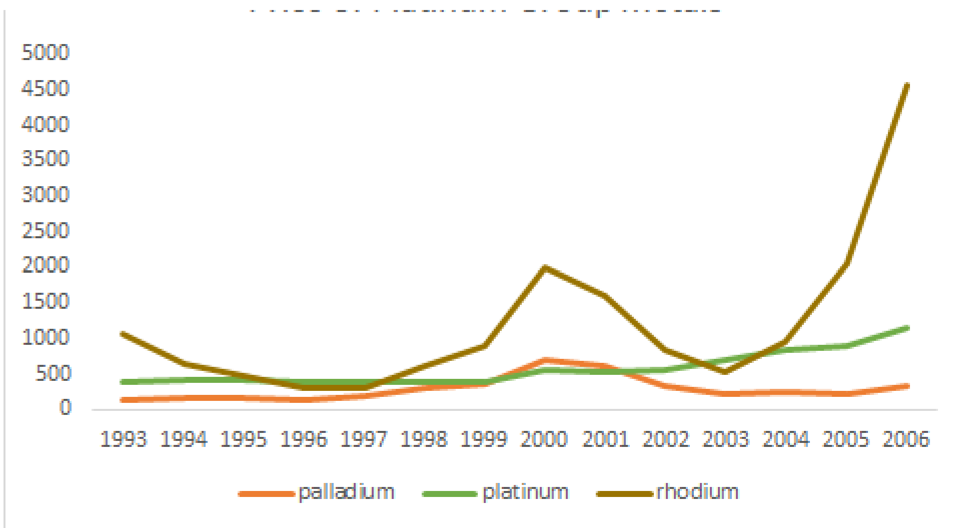


Figure 4: Price of Platinum Group Metals

In January 2008, African platinum mines were shut down for five days due to electricity generation shortages. The shutdowns incited a fear of platinum supply shortage causing the price of all PGMs including palladium to rise drastically, although not as drastically as it did previously. The prices of PGMs fell back down because mining resumed and demand decreased during the 2008 economic downturn. In 2009-2010, average palladium prices rose higher than those of 2008 again due to an increased demand from the resurging automotive industry (USGS 2010). In 2012 palladium's use in the auto industry rose to an all-time high due to an increase in Japanese vehicle production in response to the March 2011 earthquake and tsunami (USGS 2012). Around this time, auto sales shot up due to the need for replacement of cars damaged in the earthquake. Palladium continued to have a strong demand and tight supply due to its rarity into 2013, making palladium the only platinum group metal which experienced an average annual price increase in 2013 (USGS, 2013).

Tungsten

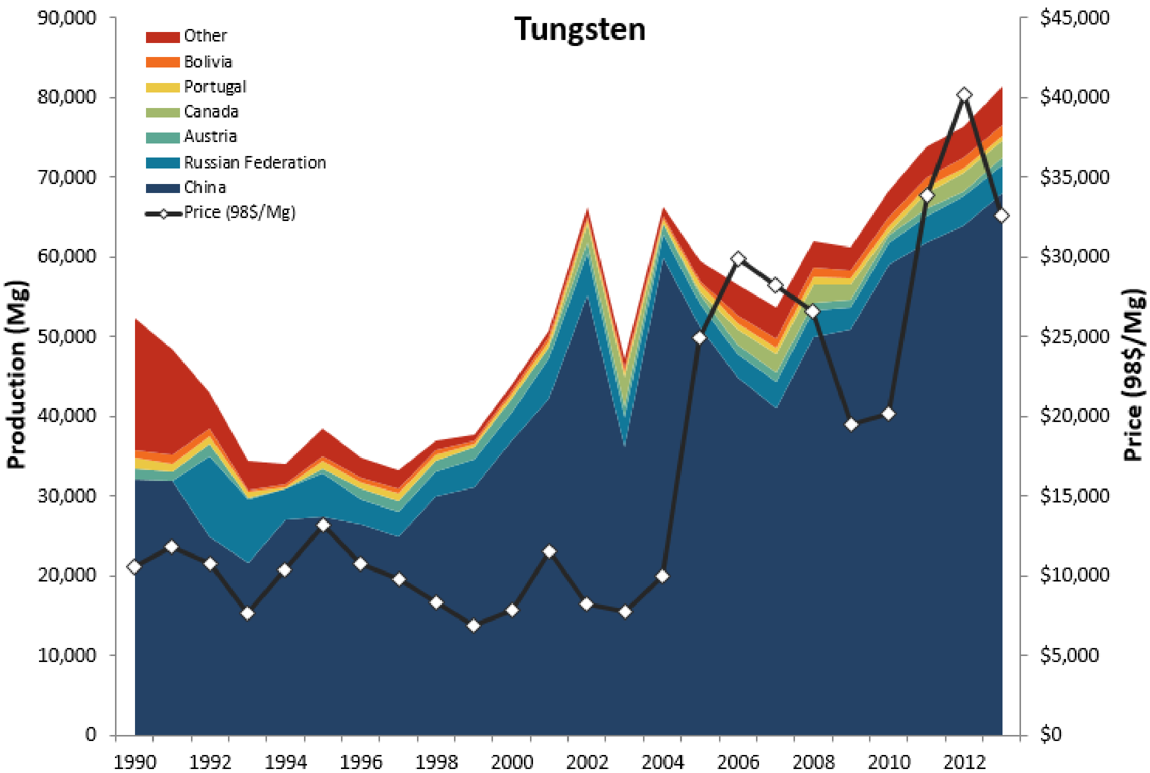


Figure 5: Price and Production of Tungsten from 1990 to 2013 (NSTC 2016)

Tungsten is the chemical element with the highest melting point and it is often alloyed with other metals to strengthen them (Emsley 2011). Tungsten is primarily used in industrial alloys, drill bits, blades, and abrasives due to its high wear resistance and melting point (USGS 2004). In particular, tungsten carbide is extremely durable and is very important to the drilling, mining and oil industries (Emsley 2011). There are few substitutes to tungsten with the exception of molybdenum, titanium, and ceramics but none of these are capable of being used in higher temperature applications than tungsten.

Historically, the price of tungsten has fluctuated greatly depending on the economic, political and social status of China, the main supplier of this ore. Tungsten is not traded via any of the traditional methods such as the London Metal Exchange;

instead sales are arranged by traders and consumers (USGS 2010). Any prices published by trade journals are just estimates based on information derived from these traders and consumers, thus the potential for bias cannot be excluded when examining this material.

By 1994, most of the production of tungsten was concentrated in China, and the Chinese mines were not producing at high rates due to relatively low prices of tungsten concentrates. Later in 1994, demand for tungsten began to rise because as the world economy improved, tungsten was being used much more often in the manufacturing industry, leading to a sharp increase in the price of tungsten concentrates (Maby, 1995). Consequently, governments such as Kazakhstan, China, and Russia increased mine production, and released a large amount of tungsten from their tungsten stockpiles. By 1996, the market was flooded with tungsten and prices dropped again (Bunting, 1997).

Up until 1999, prices continued to decrease due to high production of tungsten, and China began to increase their consumption of tungsten which continued through 2010. In early 1999, China listed tungsten as a metal under state protection, imposing restrictions on mining, export, and processing (Huang 2009). These restrictions began with stricter control over their domestic tungsten industry in order to “ensure supplies to meet anticipated domestic demand” (USGS 2010). They accomplished this goal over the next 12 years by “closing illegal mines; limiting the number of exploration, mining, and export licenses; limiting or forbidding foreign investment; imposing constraints on mining and processing; establishing quotas on mine production and exports; adjusting export quotas to favor value-added downstream materials and products; and shifting from export tax rebates to export taxes” (USGS 2010). Between 2000 and 2001, tungsten concentrate prices increased partly due to Chinese regulations, and was exacerbated by panic buying and consumer stockpiling (USGS 2010).

In 2004, China ceased the exportation of tungsten concentrates in order to provide supply for their domestic industry. There were also droughts in the southeastern regions of China which caused energy shortages, affecting mine output. Additionally China closed mines for other environmental reasons and withdrew of mining subsidies.

All of these factors led to a steep increase in global tungsten prices and a tripling in the prices of tungsten concentrates. In response to these high prices, there was an increased interest in opening new mines and finding new sources of tungsten by countries outside of China. Around 2007, as a result of the increased production of tungsten, prices lowered but never quite returned to their pre-2000 prices. This lowering in price was also aided by the economic downturn having a significant impact on the global economy in 2008.

Tantalum

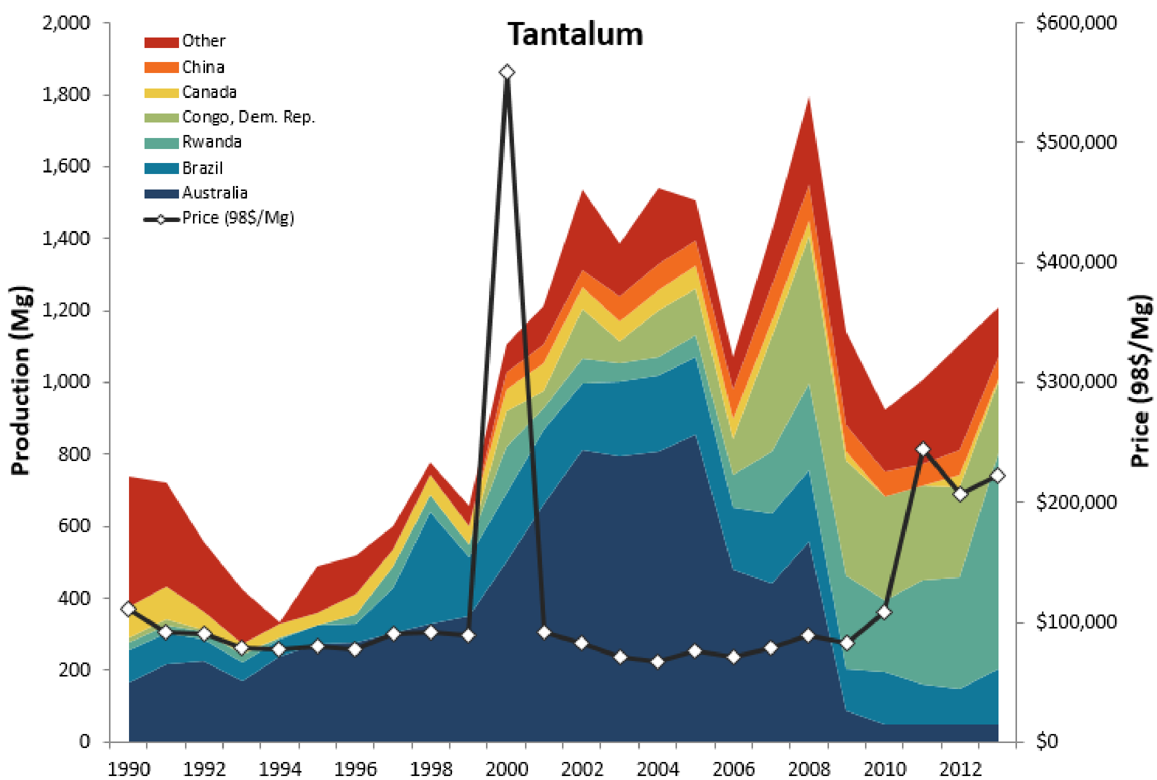


Figure 6: Price and Production of Tantalum from 1990 to 2013 (NSTC 2016)

Tantalum is primarily used in capacitors due its heat and corrosion resistance. There are substitutes for tantalum capacitors such as silicon capacitors, but they are not as effective and were not commonplace in the early 2000s. However, tantalum also has uses in medical technology, metalworking tools, and jet engine components, and for these applications, columbium, aluminum, ceramics and platinum can be used (USGS 2001).

In 2000, there was a large spike in tantalum prices. This resulted from a double and triple ordering of tantalum in 2000, due to a perceived upcoming shortage in supply (USGS 2012). The increased ordering led to beliefs that demand was increasing, reinforcing speculation that supply would not meet demand, especially from the booming electronic industry. The fact that the expected shortage did not come to fruition, combined with a weaker-than-expected demand from the electronics market, downturn in global economy, and increased tantalum inventories led to the price falling back down (USGS 2002).

More recently, in 2008, three companies that were responsible of one half of all tantalum ore production stopped production (USGS 2012). This led to another price spike. Tantalum that came from the Congo became more prevalent. However, the mainstream industry looked for a way to ban the usage of this illegal mining. The economic and financial problems in 2008 and 2009 caused 40 percent of all tantalum production to shut down as well (USGS 2012).

Tin

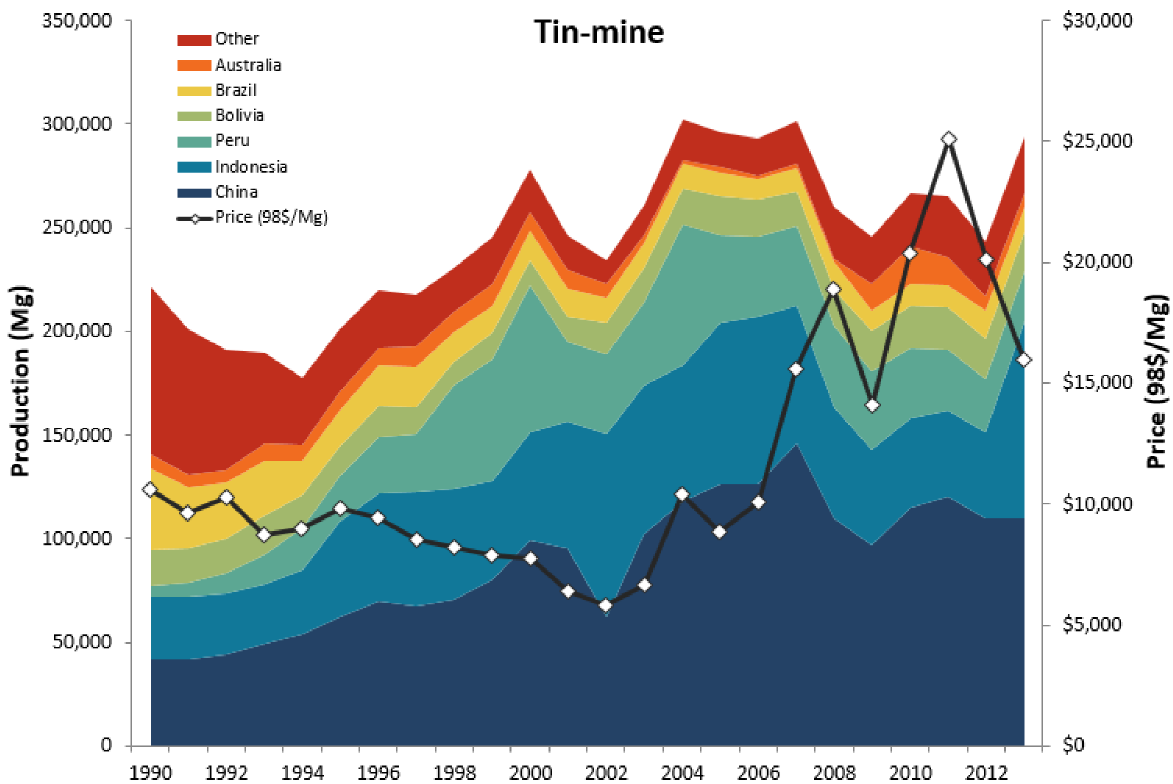


Figure 7: Price and Production of Tin from 1990-2013 (NSTC 2016)

Tin is an element which has multiple uses ranging from electronics to transportation. Tin has multiple substitutes depending on the application, including aluminum, glass, and other alloys. However, the substitutes generally are not as effective and/or are more expensive (USGS 2008).

Price spikes began in 2007 when the top two global producers of tin, China and Indonesia faced shortfalls. Shortfalls began in China with difficulties obtaining feedstock for their smelters (USGS 2009). Then in 2012, China experienced shortfalls in production because of mine disasters and flooding (USGS 2012). In 2012, Indonesian mines experienced shortfalls because the Indonesian government raised the standard purity of tin produced in Indonesia, which forced Indonesian factories to decrease production as they upgraded their smelters. There was also a government crackdown on illegal production sites in Indonesia. There was also increased global demand resulting from the replacement of lead with tin in multiple applications. In 2016, Increased production of tin as well as decreased demand from China led decrease to the decrease in tin prices (USGS 2016).

Nickel

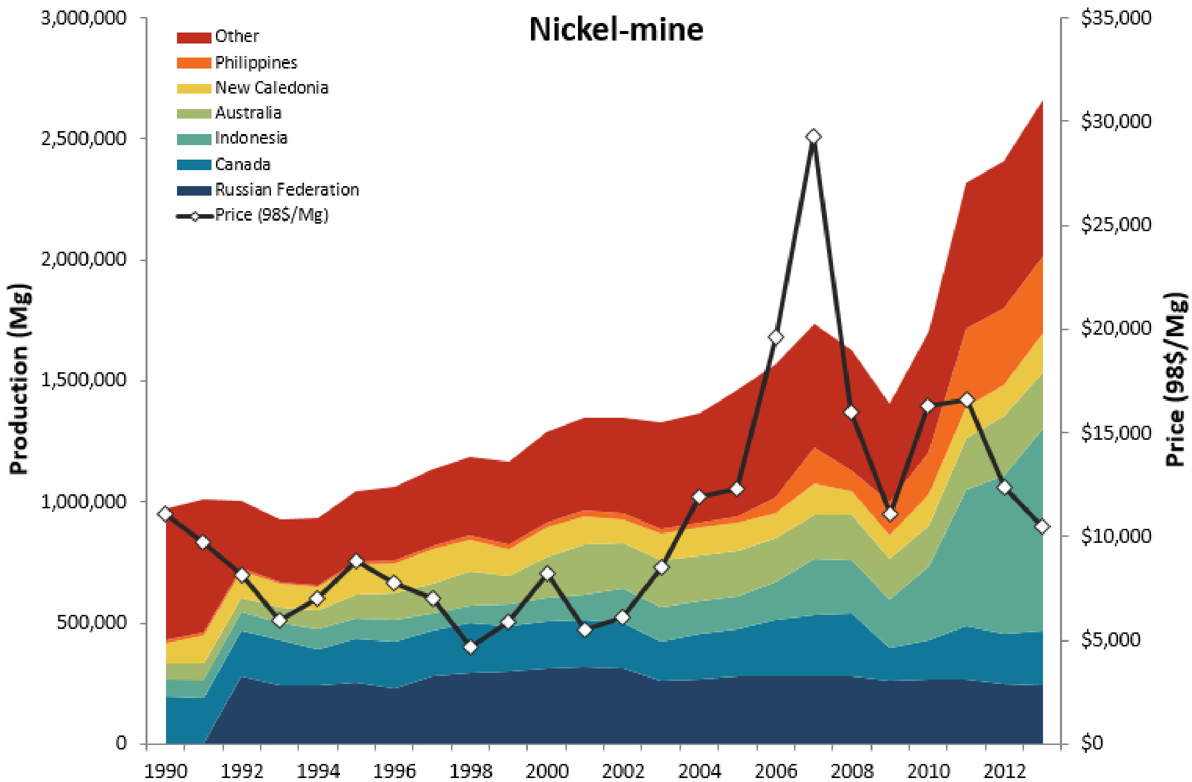


Figure 8: Price and Production of Nickel from 1990-2013 (NSTC 2016)

Nickel is a transition metal element. Nickel's most common application is in stainless steel production, with addition demand stemming from its use in engines, and in hybrid batteries,. Potential substitutes for nickel include aluminum, steels, plastics, titanium alloys, and lithium. Nickel allows for more efficient engines due to its ability to withstand stress at high temperatures. In addition, nickel is used to created light-weight alloys for use in vehicles.

Starting in 2006, nickel prices began to rise as supply struggled to meet demand. This was due to an increase in nickel-metal hydride battery and stainless steel production, while new mines were still under construction and not operational. Demand for nickel was high in 2006, due to high quantities of steels and other alloys being produced, and spot prices for refined nickel were historically high in early 2007, due to low stockpile levels at the beginning of the year (USGS 2005-2008). The price spike also had to do with increased demand for more efficient engines which made use of nickel alloys. The price dropped in late 2007, as demand lowered due to recycling of stainless steel scrap. Use of nickel decreased with the rise in prices with nickel being substituted with cheaper materials

Tellurium

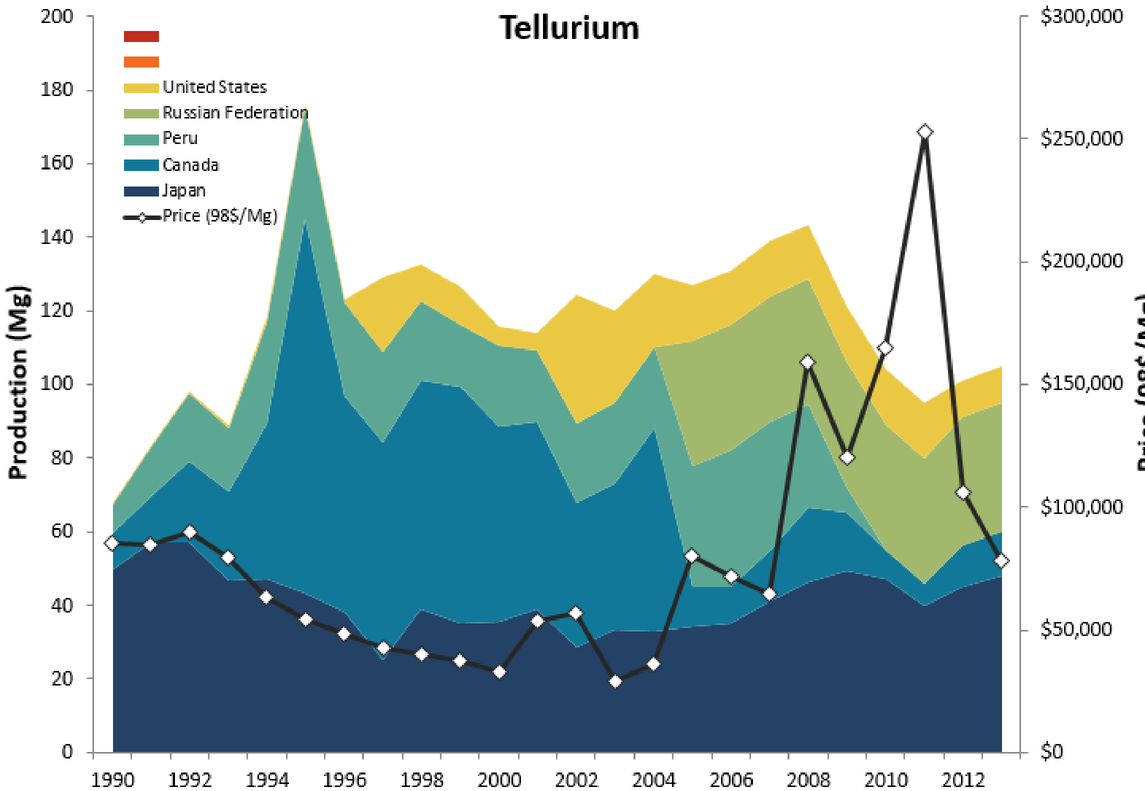


Figure 9: Price and Production of Tellurium from 1990 to 2013 (NSTC 2016)

Tellurium is a semiconducting metalloid element. It is produced as a byproduct of the refining of copper. Around 80-90% of the world's tellurium comes from copper anode slime electrolysis. The main use of tellurium is high purity tellurium for electronic applications, and solar panels make up 40% of global consumption of tellurium (USGS 2011). Tellurium's other application are its usage in semiconducting alloys to improve machining alloys. Substitutes for tellurium include bismuth, phosphorus, selenium, sulfur, and calcium.

As thin-film solar panels hit mainstream production in 2008, the price of tellurium spiked dramatically as demand hit never-before-seen levels at the same time Peru, major producer of tellurium, decreased output significantly as it was not economically feasible for production. In 2012, the combination of the end of tax rebates for solar panels in Europe, and the growth in availability of cheaper silicon-based cells substantially lowered demand for tellurium (USGS 2012). As a result, prices fell back to pre-2008 levels.

Rare Earths

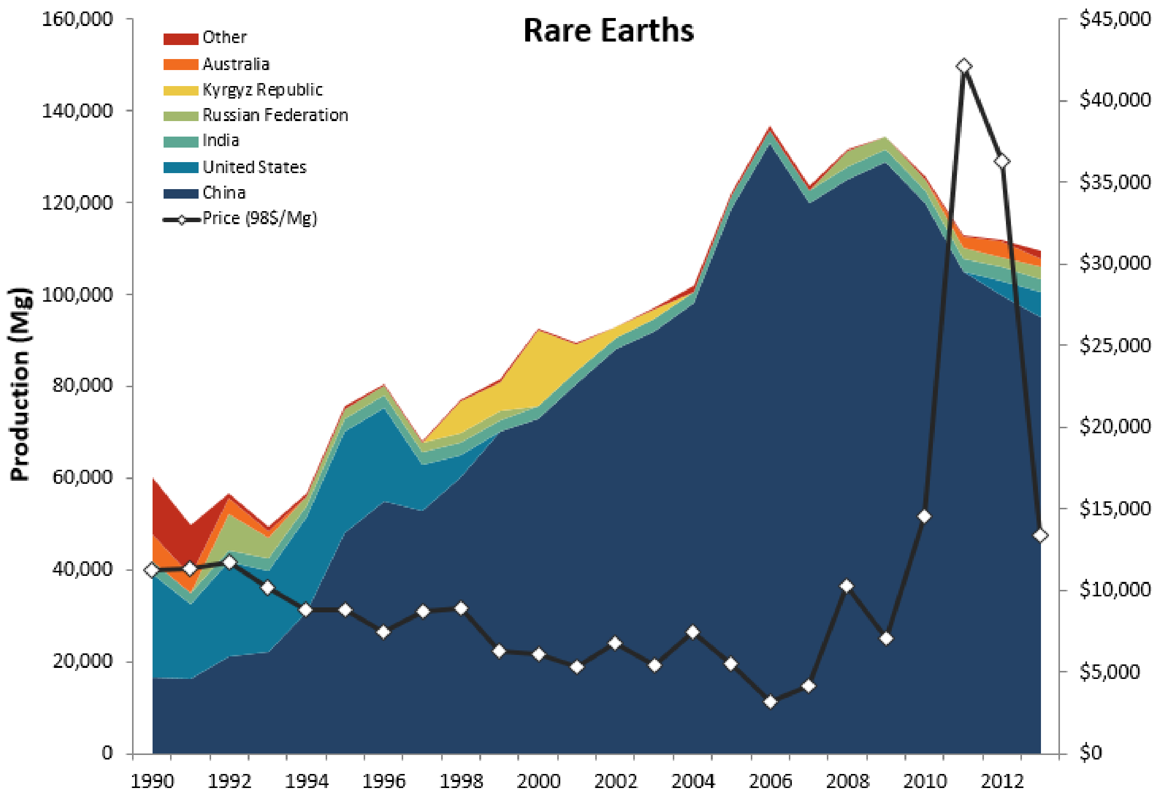


Figure 10: Price and Production of Rare Earths from 1990-2013 (NSTC 2016)

Rare earth metals are a group of elements that have a wide range of uses including chemical production, alloys, petroleum refining, automotive catalytic converters, glass and ceramics, and electronics. The DOE has already researched and covered rare earth metals in great detail. In our report and analysis, it serves as an effective baseline and is good for comparison purposes.

While consumption of rare earth metals fluctuated, from 2000 until 2012, the trend of usage increased overall. This trend is mostly due to their extensive use in the production of catalytic converters, permanent magnets, and rechargeable batteries for electric and hybrid vehicles. Rare earths faced short domestic supply from 2001 to 2007, because of the closure of a separation plant in Mountain Pass, CA. During this period, domestic consumers of rare earth metals relied heavily on imports. The price rose even more rapidly from 2010 to 2012, caused by decreasing worldwide supply and increased demand (USGS 2000-2012). This decrease in worldwide supply was due mainly to restrictions on export of rare earth metals in China, the main producer of rare earths, in an attempt to increase the availability of such materials to internal companies.

Common Trends and Drivers

While many materials have been researched in this project, each with its own origins and uses, there have been some trends and causes of anomalies that have appeared in multiple instances.

In many cases there was a disruption of the material's supply chain. Supply Chain Disruptions, as we call them, are sudden changes to supply chain without warning, such as due to natural disasters or military conflicts. Natural disasters such as hurricanes or droughts are often impossible to predict and even harder to prevent. They can result in the closing of mines such as in the case of tungsten where Chinese mines shut down in 2004 due to a drought causing a disruption in energy production.

One driver that we saw with a few different materials was a situation where a government's actions having an effect on a material's market. We refer to this driver as Government Action. For example, China's tariffs and quotas on tungsten caused a generally higher price over a long period of time. Government action can have long lasting effects on a material's market, causing many different outcomes.

In several cases, the development of a new technology or expanded use of an existing technology caused demand for a specific material to increase, putting strain on the supply chain. We refer to this as Market Dynamics. Examples of this are tellurium's use in thin film photovoltaic cells and palladiums use in catalytic converters. In the case of tellurium, companies then overcompensated for demand, resulting in the market being flooded causing several producers to shut down or go bankrupt. There were also instances where perceived shortages, based purely on speculation, had real world repercussions as was the case with tantalum. Shown below in Table 3, is an overview of all the material market anomalies studied, with their years of anomaly, and their causes of potential criticality.

Material	Anomaly Years	Supply Chain Disruption[1]	Government Action[2]	Market Dynamics[3]
Palladium	1999-2001			X
Tungsten	2004-Present	X	X	
Tantalum	2000-2001			X
Tin	2007-2010	X	X	X
Nickel	2006-2008			X
Tellurium	2008-2011			X
Rare Earths	2006-2013		X	X

[1]Any sudden changes to a supply chain without warning, including natural disasters, strikes, and military conflicts
[2]Changes in government policy regarding materials such as tariffs on imports and exports, mining subsidies, quotas on mining/production/exportation
[3]Changes in the market including global recession, speculation by investors, supply not/barely meeting demand due to a delayed response or lack of minable sources

Table 3: Historic Cases of Material Market Anomalies

4.2 Analysis of Tool Performance

To test the performance of the IST as an early warning screening tool for potential material criticality, we compared the seven cases of material market anomalies described in Section 4.1 against the results of the tool and examined reasons why the tool did or did not detect these anomalies. To counteract any identified shortcomings, several methodological adjustments were tested. This included varying the time period over which potential criticality is calculated as well as the relative weights of each indicator.

Important note: To determine whether a material is potentially critical or not, a threshold value of 0.335 was calculated and used by the NSTC. With our changes in the methodology, that threshold would change as well. It is also important to say that the conclusions reached are only true for the materials represented here. Further analysis is needed to see if these changes hold true for all of the materials represented in the IST.

4.2.1 Current Performance of the IST

Material	Anomaly Years	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
Palladium	1999-2001	*0.35*	*0.37*	*0.39*	*0.36*	*0.36*	*0.37*	*0.4*	*0.36*	0.27	0.24	0.23	0.27	0.28	0.27	0.28
Tungsten	2004-Present	*0.34*	*0.36*	*0.36*	*0.38*	0.32	*0.4*	*0.52*	*0.48*	*0.41*	*0.46*	*0.37*	0.33	*0.36*	*0.41*	*0.4*
Tantalum	2000-2001	0.17	*0.41*	*0.43*	*0.44*	*0.42*	*0.42*	*0.4*	0.14	0.12	0.15	0.14	0.15	0.28	0.24	0.26
Tin	2007-2010	0.16	0.18	0.19	0.2	0.2	0.24	0.25	0.26	0.32	0.28	0.22	0.24	0.25	0.21	0.23
Nickel	2006-2008	0.17	0.16	0.16	0.15	0.15	0.16	0.16	0.18	0.2	0.18	0.18	0.18	0.2	0.22	0.19
Tellurium	2008-2011	0.2	0.16	0.18	0.18	0.19	0.21	0.26	0.26	0.25	0.3	0.27	0.26	0.27	0.26	0.25
Rare Earths	2006-2013	0.31	0.31	*0.36*	*0.39*	*0.38*	0.32	*0.34*	*0.45*	*0.45*	*0.5*	*0.5*	*0.52*	*0.58*	*0.54*	*0.48*

Table 4: Summary of Criticality Values for Historic Cases of Material Market Anomalies (Data source: NSTC 2016)

As the IST is currently, it is quite able to detect potential criticality, or at least see it as it occurs, for fairly niche materials. As shown in Table 4, the IST recognized potential criticality in four out of seven of the historic cases of material market anomalies. Of these four, three (palladium, tantalum, and rare earths) would be considered very niche. The fourth, tungsten, is fairly ubiquitous because of its ability to strengthen alloys. This exception is likely due to tungsten’s lack of suitable replacements, as well as the fact that its primary producer is China. The IST did not detect potential criticality for tin, nickel, and tellurium. Both tin and nickel are fairly common metals, but tellurium is not. It has a fairly niche application within the electronics and solar cell markets. The reason for this exception is likely that it has several substitutes, allowing the market to better cope with rapid changes in supply and demand. (NSTC 2016)

A major note to make about that IST is that, for the cases that we looked at in which the tool recognized potential criticality, it was just as likely to detect the potential criticality before a market anomaly as it was to not recognize the potential criticality until the anomaly occurred. Looking again at the four cases of material market anomaly that the IST recognized, two of them were identified just as the anomaly occurred, and the other two were detected ahead of time.

The last major observations of the IST's results is on how long it reports potential criticality, and how consistently. The IST has the tendency to report potential criticality long after the anomaly has been corrected. In the cases of palladium and tantalum, the IST continued to report potential criticality for five and four years, respectively, following the end of the market anomaly. These extensions can be fairly detrimental, because they would suggest that more time, money, and effort needs to be put into observing these materials than necessary. Conversely, the IST can also report gaps in potential criticality, suggesting, in cases like tungsten, that the material can be ignored and more money, time, and effort can be spent on other materials.

4.2.2 An Analysis of Indicators

Through an analysis of the individual indicators that influence the potential criticality (C), several observations were made that could help solve some of the issues noted in Section 4.2.1. As a brief reminder, these indicators are R, the supply risk indicator (geopolitical concentration of production), I, the production growth indicator, and M, the market dynamics indicator (price volatility). R measures supply risk by using the WGI and HHI to calculate a value that both shows a country's stability and its concentration of a material's production market. I uses primary production growth over five years to calculate a value for how much the material's production has increased. M uses price data over five years to calculate a value that represents how volatile a material's price is. All of these indicators are then normalized between 0 and 1.

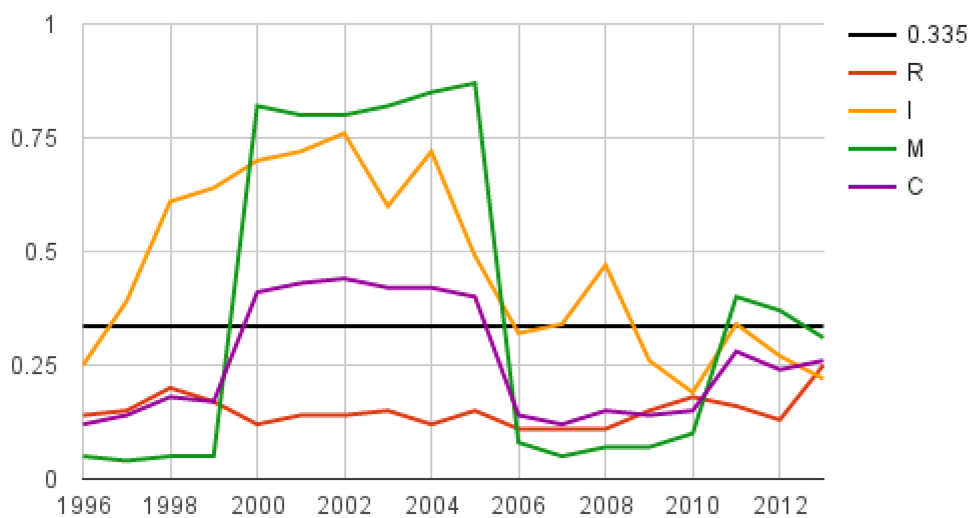
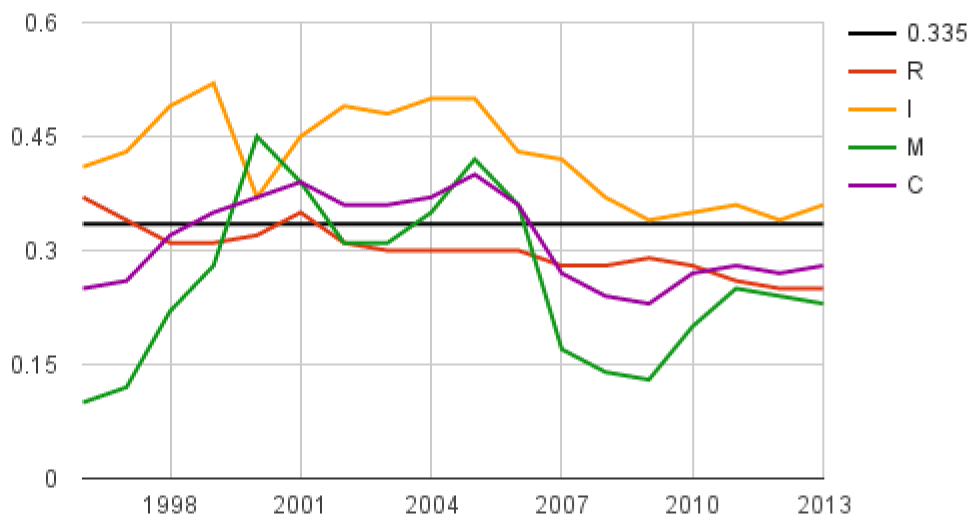


Figure 11: Tantalum Indicators, 1996-2013 (Data source: NSTC 2016)

Tantalum provides an excellent example of the observations that were noted regarding the indicator variables, shown Figure 11. Tantalum's market anomaly began in 2000, and the IST was only able to report potential criticality starting in the same year. After looking at the indicators, it is clear that the I indicator increased by nearly 3 times in the years preceding, and the R indicators remained low but consistent. The M indicator is where a problem can be found. M increased by an enormous amount, but only starting in the year that the anomaly occurred. As stated before, M is the market dynamics indicator, which is measured using price volatility. As price hikes usually occur when a market anomaly actually happens, and not before, the volatility doesn't increase until the anomaly occurs. For tantalum, because M was so low before the anomaly, and it jumped so high when the anomaly occurred, the C value is forced to follow the trends introduced by the M indicator. Thus, despite the I value being fairly high before the



anomaly, the potential criticality does not break the threshold until 2000.

Figure 12: Palladium Indicators, 1996-2013 (Data source: NSTC 2016)

When looking at palladium, see Figure 12, it is obvious that it is another example of M playing catch up. For palladium, I begins high, and then continues to rise. M, on the other hand, begins fairly low and then rises. In 1999, when the C value breaks the threshold for potential criticality (0.335) I had simply reached a high enough point for it to counteract the low M. However, that is not the most import thing to note about M for palladium. If one followed the general trends of M, and compared those trends to the trends of the C value, there is a distinct similarity between them. The trends of I have an effect on C, usually raising the C value, but M still seems to have a stronger effect on the final C values.

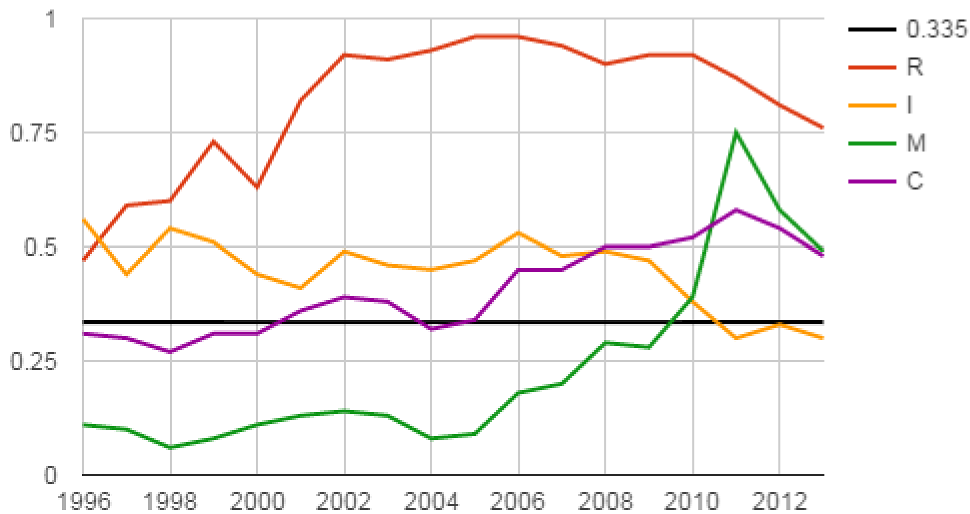


Figure 13: Rare Earths Indicators, 1996-2013 (Data source: NSTC 2016)

Rare earths provide an interesting example, which can be seen in Figure 13, and is being included specifically because the IST has already been proven efficient for this case (NSTC 2016). For rare earths, R has a much larger value than the other indicators. This should drive the C value up, which it does, but doesn't have as much of an impact on the trends of C as one might think. Just as it was with palladium and tantalum, the trends of the C value seem to be very similar to the trends of M indicator. In this case, however, it doesn't drag it down like it had with others. The R value is simply too high for that to happen.

From these three examples, it's clear that M has too strong of an impact on the final C value, typically suppressing it until the material market anomaly occurs. If one was to look at the indicators besides the C value, it can be observed that the I indicator is usually high or rising preceding a material market anomaly. However, the M indicator is usually stable and very low at any time other than during an anomaly. Among the seven cases of historic material market anomalies, the low M indicator was able to cancel out the I indicator almost completely, resulting in the IST not reporting potential criticality until the anomaly has already occurred. Of course, the R indicator affects this statement, because, as it was with rare earths, if the R indicator was high enough the IST would still be able to report the potential criticality.

4.2.3 Recalculating C

After going over the results of the analysis of indicators, we decided that the best method to attempt to remedy the issues that we observed was to change the relative weights of the indicators. As a reminder, C is currently calculated using the geometric mean of the three indicators, or $C = \sqrt[3]{R * I * M}$.. When using different weights with the geometric mean, the calculation becomes the weighted geometric mean, or $C = (R^{W_1} * I^{W_2} * M^{W_2})^{1/\sum_1^3 W_N}$ The first thing we tried was removing M. This is the same as applying a weight of zero to M, resulting in $C = \sqrt{R * I}$. Then, we tried using two full sets of weights, with Set 1 being w_1=1, w_2=4, and w_3=¼, and Set 2 being w_1=1, w_2=2, and w_3=½. These weights were chosen for their simplicity and because they would show trends that could then be used to justify further experimentation. As we had observed that I generally was more helpful when looking for potential criticality and M was not, we decided that for these two sets we would increase the weight on I by the same factor we would decrease the weight on M.

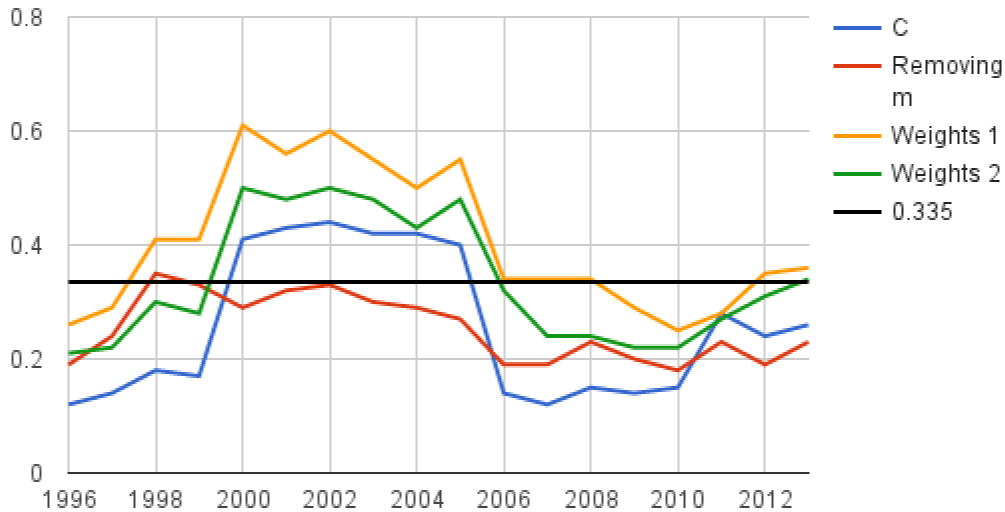


Figure 14: Alternative C Calculations for Tantalum, 1996-2013 (Data source: NSTC 2016)

As tantalum was our strongest example when showing how M negatively impacted the potential criticality value, we have chosen it as the prime example for the changes in the calculation of C as well. From looking at the comparison of the results of our modified weighting with the original C value (Figure 14), the effects are more than evident. When M was removed entirely, the C indicator value only once broke the threshold for potential criticality, but that year is two years before the period of anomaly. So, while it was not overly beneficial, we were able to remove the detrimental trends that M introduced. The two other sets of weights proved much more interesting. For the second set of weights, where we increased the weight on I and decreased the weight on M by 4, the IST would be able to detect the anomaly period two years in advance. The trends of the M indicator are still evident, but the effect of them has been significantly reduced. For the third set of weights, where we increased the weight on I and decreased the weight on M by 2, the IST would have been unable to report potential criticality before the anomaly period, but the weakening of the effect of M on C is evident.

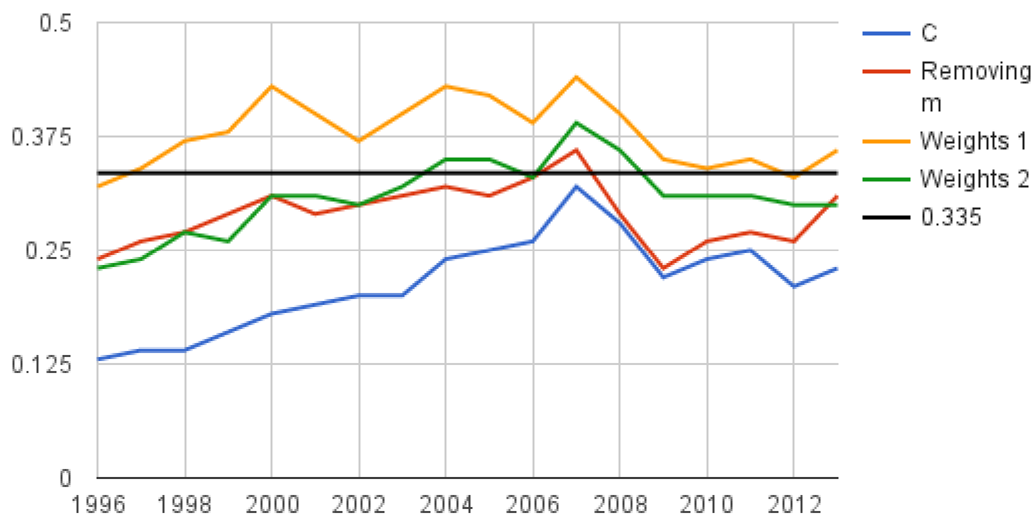


Figure 15: Alternative C Calculations for Tin, 1996-2013 (Data source: NSTC 2016)

We chose tin as an example because it was not reported as potentially critical by the IST at all. It got very close in 2007, the first year of the anomaly period, which is shown in Figure 15. When we removed M from the calculation, however, the IST would have been able to report potential criticality in 2007, which is better but still not ideal. The other sets of weights proved to be much better. In the case of tin, the second set of alternative weights worked too well. Under alternative 2, the IST would report potential criticality for every year available, except for 1996 and 2012. While a false positive is significantly better than a false negative, that is simply far too many years in comparison to the number of years of anomaly. In this case, alternative 3 provides better results. Under alternative 3, the IST would have been able to detect potential criticality as early as three years prior to the period of anomaly. However, the period of potential criticality would have ended before the period of anomaly did.

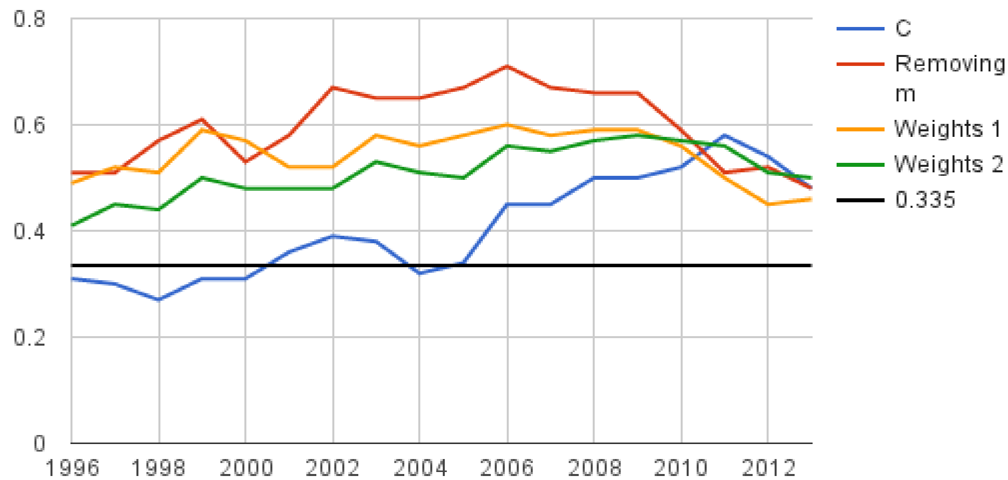


Figure 16: Alternative C Calculations for Rare Earths (Data source: NSTC 2016)

Rare earths provide one of the more interesting cases when we modified the calculation of C, see Figure 16. Rare earths is one of only two materials, the other being tungsten, that had the potential criticality increase more dramatically by removing M then by applying one of the other sets of weights. However, it can still be said that all three methods were identically effective. Under all three of the changes to the calculation of C, rare earths would have been reported as potentially critical by the IST from 1996 to 2013. This is because of how high the R value of rare earths is, as was the case for tungsten. When M has its weight lowered, and especially so when it is removed, the high R value takes over the calculation, increasing the C values by a large amount.

Material	Anomaly Years	Original IST	Alternative 1 (R=1, I=1, M=0)	Alternative 2 (R=1, I=4, M=1/4)	Alternative 3 (R=1, I=2, M=1/2)
Palladium	1999-2001	1999-2006	1996-1999, 2001-2007	1996-2008	1997-2006
Tungsten	2004-Present	1999-2002, 2004-2009, 2011-2013	1996-2013	1998-2013	1998-2013
Tantalum	2000-2001	2000-2005	1998-1999	1998-2005	2000-2005
Tin	2007-2010	2007*	2006-2007	1999-2007, 2013	2007
Nickel	2006-2008			2011-2013	
Tellurium	2008-2011	2008*		1996-1998, 2006, 2008	
Rare Earths	2010-2012	2006-2013	1996-2013	1996-2013	1996-2013
Detected Before Anomaly Years	Detected After Anomaly Years or Not at All	Detected During Anomaly Years	*Very Close to Threshold		

Table 5: Summary of Impact of Alternative C Calculations

On the whole, changing the weights of the indicators seems to have a beneficial effect on which years the IST would report as potentially critical. As shown in Table 5, each of the changes would cause at least one material that the IST initially reported during the anomaly period to be reported early. In addition, each of the three changes caused least one material that was initially not reported at all to be identified by the tool. Based on observations of how many materials reported as potentially critical during their anomalous period, changing the weights to alternative 2 performed the best - only Nickel was not accurately detected. However, many of the periods of potential criticality began long before the period of anomaly, and would not be helpful.

There are important facts to note. The sets of weights and methods shown above are not concrete values. They are simply sets of weights that we chose, as experimental values, to show how the changes in the calculation of C could affect the years of reported potential criticality for the seven materials we examined. There would have to be a significant amount of work done to find the ideal weights across all materials that appear in the tool. Also, as stated at the beginning of this section, the threshold value was chosen through an analysis of the initial C values. As such, changing the method by which C is calculated would also change the threshold value.

4.2.4 An Analysis of Time Period

Another key feature of the calculation of C is the time period over which the M and I indicators are calculated. The IST currently reports C values that are calculated using a period of five years by default. We decided to see if that was the best time period to use by incrementally adjusting the number of years. We then looked for periods of time that would cause material market anomalies to be detected earlier than they were initially, preferably by 2 or 3 years, and that single year holes between periods of potential criticality would not exist so as to avoid causing unnecessary confusion. In addition to looking at how the final C value was affected by the period, we also looked into how the individual I and M indicators were affected by the changing time period.

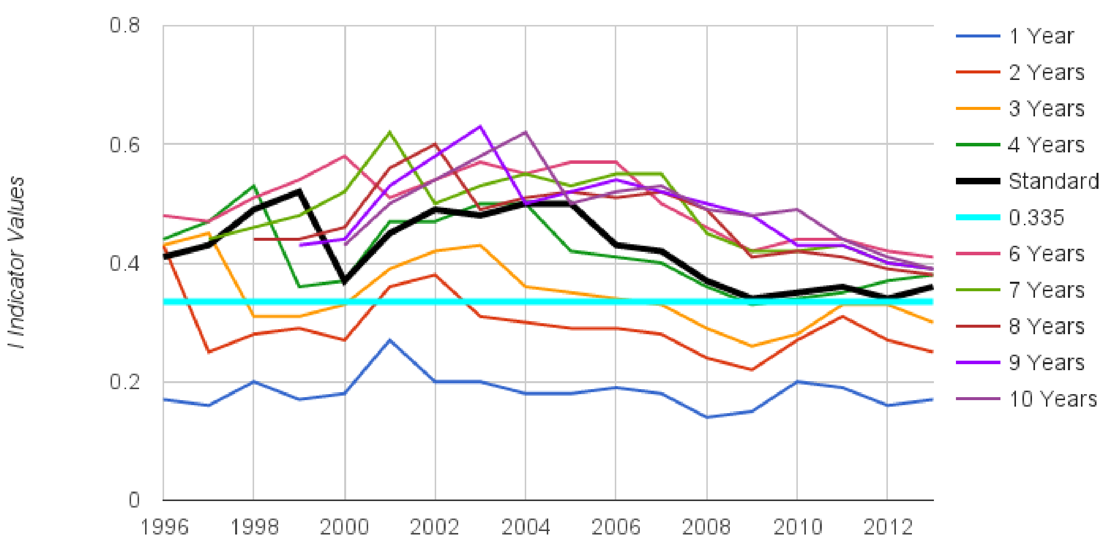


Figure 17: Impact of Time Period on I Indicator for Palladium

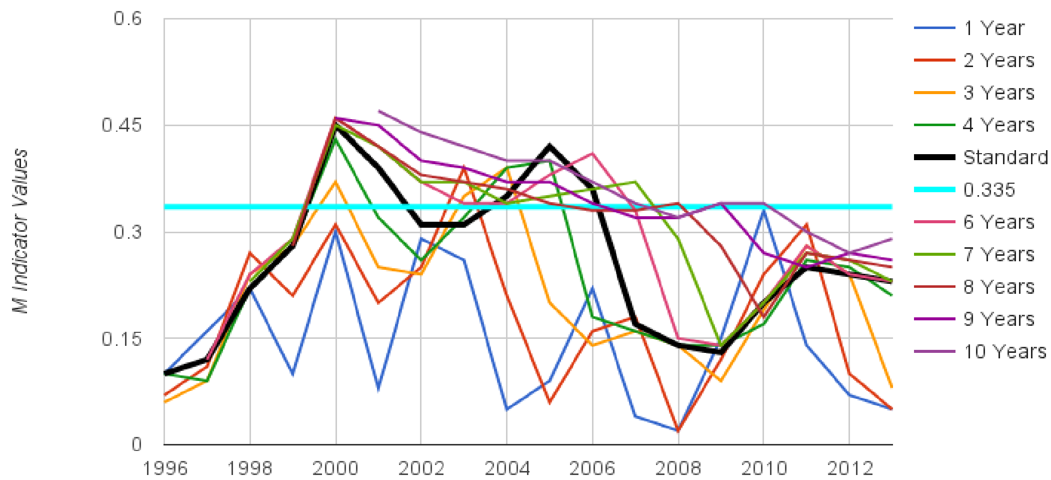


Figure 18: Impact of Time Period on M Indicator for Palladium

On the whole, changing the time period did not cause the IST to report any materials as potentially critical that were not at least close to the threshold of 0.335. Changing the time period did, however, report materials earlier. This is true for palladium, for example. For palladium, the I indicator followed a fairly simple pattern when we changed the time period, see Figure 17. If the time period was increased, the I indicator increased, and if the time period was decreased, then I decreased. This is because palladium, for the most part, has had its production increasing since 1996. So, as the time period was increased, the production growth had a larger difference to calculate over, and thus higher production growth values were reported. As can be seen in Figure 18, M is quite different. Yes, it can be claimed that M increased as the time period did, but it wasn't that simple. As the time period changed for M, the trends in the reported values changed. As the time period decreased, the values from year to year tended to jump up and down, as there were less years to calculate how much the price changed over. When the time period was increased, M values tended to flatten out, maintaining a relatively similar value for many years. This is because when more prices are used in the calculation of M, it is more likely large price spikes or dips are included.

Even if the price had been stable for many years, if the time period is long enough to included pricing data from when it wasn't, the M value would be reported high.

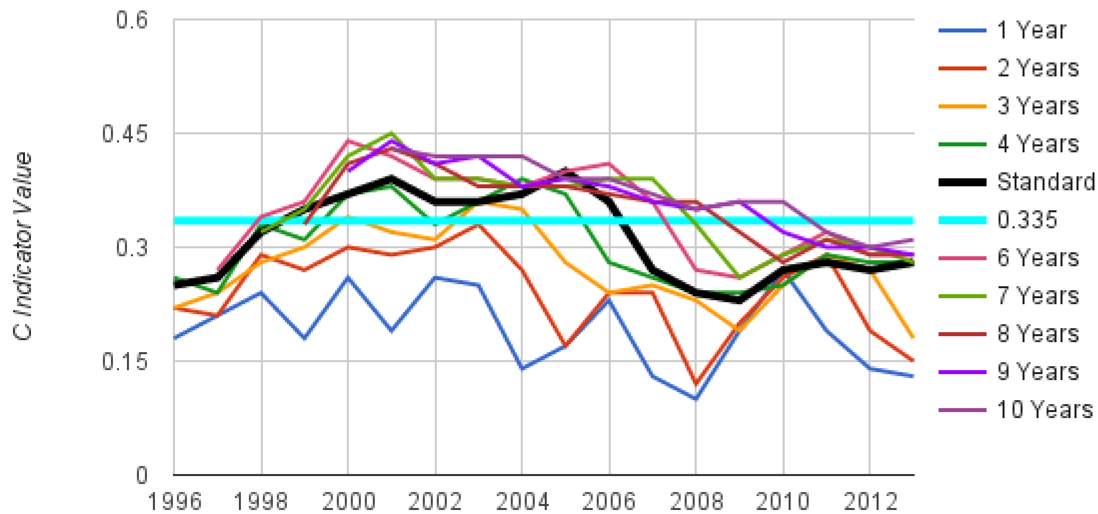


Figure 19: Impact of Time Period on C Indicator for Palladium

Period	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008
5 Years	0.25	0.26	0.32	*0.35*	*0.37*	*0.39*	*0.36*	*0.36*	*0.37*	*0.4*	*0.36*	0.27	0.24
6 Years		0.27	*0.34*	*0.36*	*0.44*	*0.42*	*0.39*	*0.39*	*0.38*	*0.4*	*0.41*	*0.36*	0.27

Table 6: C Values for Palladium with 5 and 6 Year Time Periods

For palladium, when the time period was increased, so did the C values, with the reverse also being true. However, there was a limit to the effectiveness of increasing the time period. As the time period got longer, it began to reach further back than it had data available for. Because of this, it would report 0 values. This is hard to see in Figure 19, as the lines start when the 0 values end. It can be seen more clearly in Table 6. Changing the time period to six years allows the IST to report palladium as potentially critical a year earlier than normal, two years prior to the anomaly year, see Table 6. It also balances the data atrophy that occurs as more and more blank spaces begin to appear in the charts.

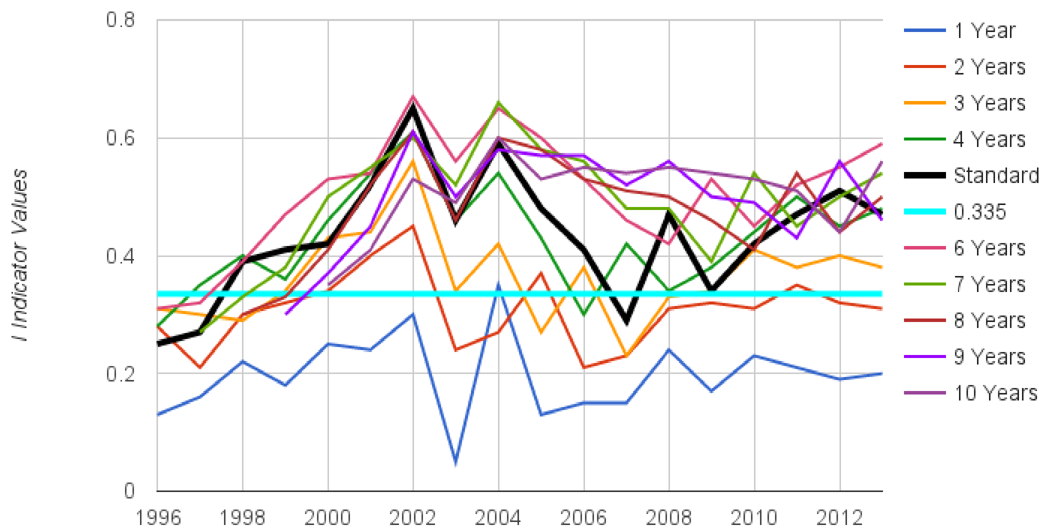


Figure 20: Impact of Time Period on I Indicator for Tungsten

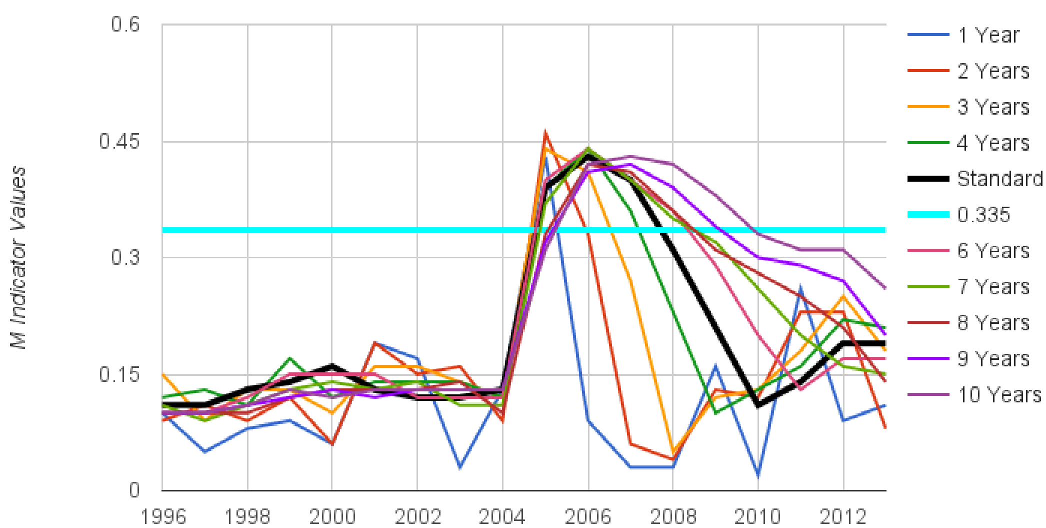


Figure 21: Impact of Time Period on M Indicator for Tungsten

For tungsten, the I and M indicators follow very similar trend to palladium, but the same settling trend that was previously noted in the M value can be noted in tungsten's I indicator, see Figure 20. It is true that as you increase the time period, the I value increases, but the amount it increases by goes down with every year. This also holds true for M, which can be seen in Figure 21.

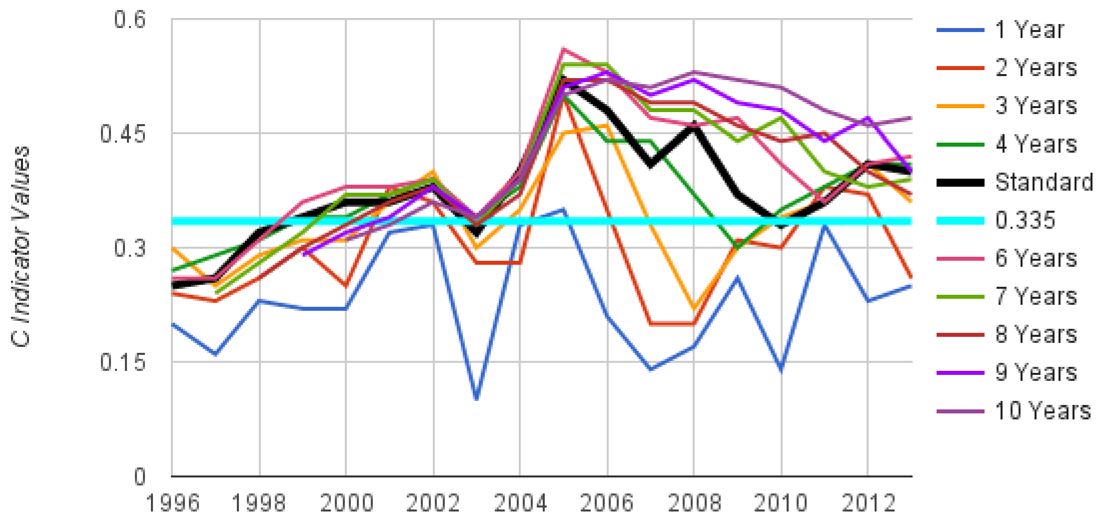


Figure 22: Impact of Time Period on C Indicator for Tungsten

Period	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
5 Years	*0.34*	*0.36*	*0.36*	*0.38*	0.32	*0.4*	*0.52*	*0.48*	*0.41*	*0.46*	*0.37*	0.33	*0.36*	*0.41*	*0.4*
6 Years	*0.36*	*0.38*	*0.38*	*0.39*	*0.34*	*0.4*	*0.56*	*0.53*	*0.47*	*0.46*	*0.47*	*0.41*	*0.36*	*0.41*	*0.42*

Table 7: C Values for Tungsten with 5 and 6 Year Time Periods

Tungsten provides an example of the other criteria we were looking for in our analysis of year, see Figure 22. When the time period is increased, the gaps that appear at 2003 and 2010 are no longer present, which can be seen in Table 7. Values above the 0.335 threshold before 2004 could be viewed as a very long period of false positives, as the anomalous period we decided upon hadn't occurred yet. As with palladium, a time period of six years provides what we were looking for. That is, an early warning to the material anomaly and that one year gaps were removed. As the time period increases beyond six years, those gaps are reintroduced along with 0 values appearing on the chart.

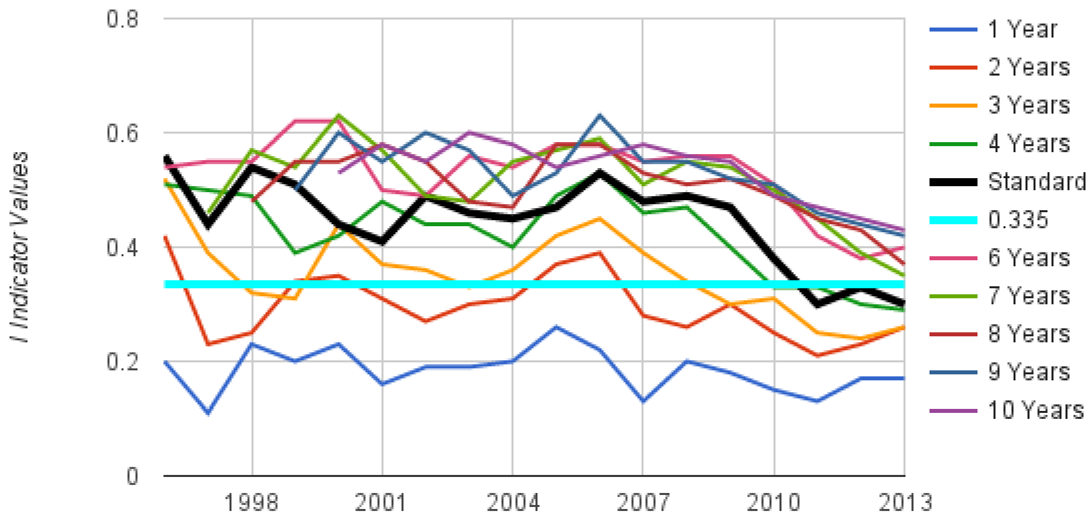


Figure 23: Impact of Time Period on I Indicator for Rare Earths

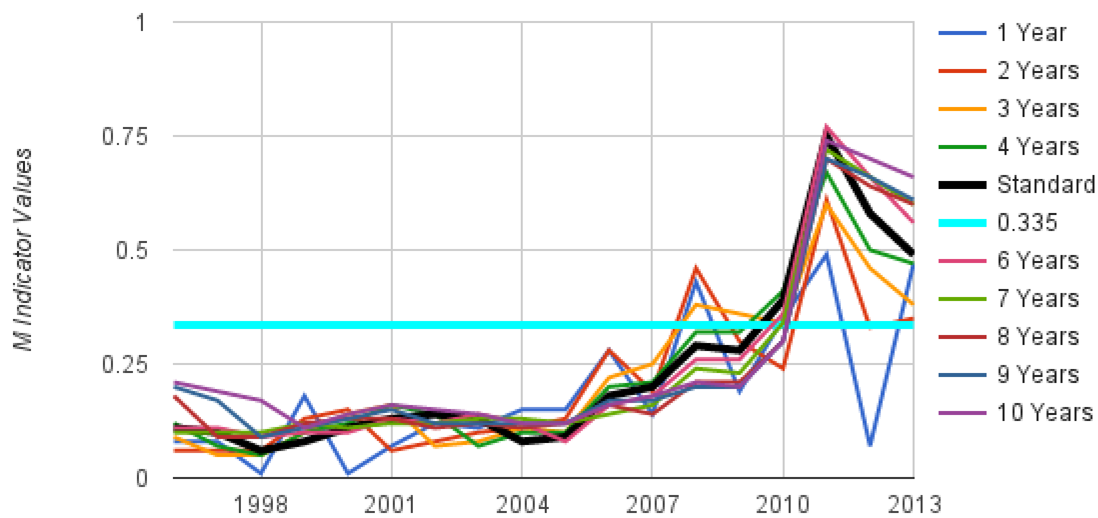


Figure 24: Impact of Time Periods on M Indicator for Rare Earths

In the case of it's I and M values, rare earths are more difficult to explain than its C values. I still maintains the qualities that were mentioned previously: As the time period increases, so does I, as well as the reverse, and that as the time period gets larger, the increase from year to year gets smaller, see Figure 23. M, however, is more difficult to find a trend for. For the majority of the time between 1996 and 2013, the M values that are produced when the time period is changed are very similar. As shown in Figure 24, they cluster so tightly that it is difficult to determine trends. This is because the price of rare earths remained so constant for so long that no matter how you change the time period, it doesn't include any price values that increase M.

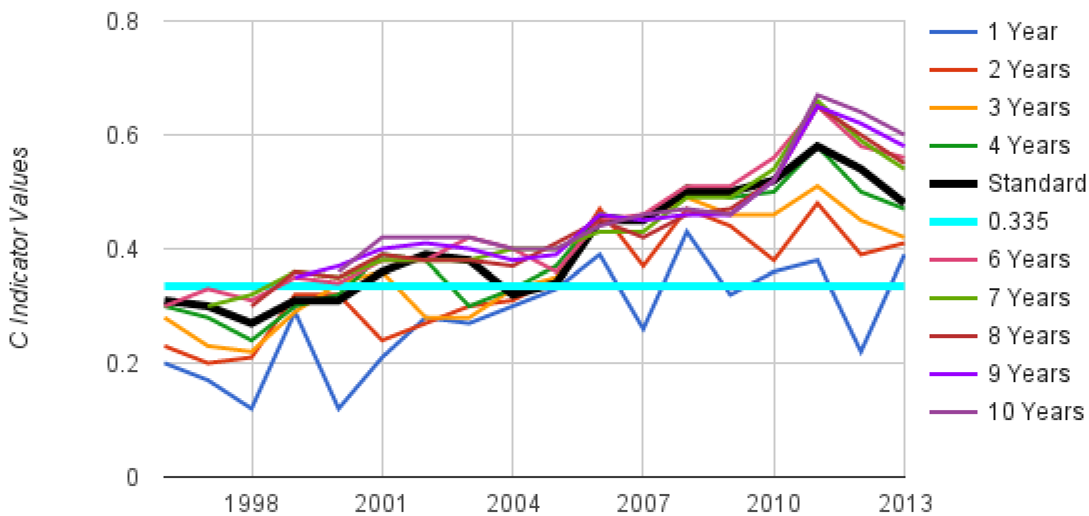


Figure 25: Impact of Time Period on C Indicator for Rare Earths

Period	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
5 Years	0.31	0.31	***0.36***	***0.39***	***0.38***	0.32	***0.34***	***0.45***	***0.45***	***0.5***	***0.5***	***0.52***	***0.58***	***0.54***	***0.48***
6 Years	***0.35***	***0.34***	***0.38***	***0.38***	***0.42***	***0.4***	***0.36***	***0.45***	***0.46***	***0.51***	***0.51***	***0.56***	***0.65***	***0.58***	***0.56***

Table 8: C Values for Rare Earths with 5 and 6 Year Time Periods

When it comes to C values, changing the time period of rare earths has both effects we desired when we started looking at the time period, which can be seen in Figure 25. When the time period is increased, IST reported potential criticality as far back as 1999, and the single year gap in 2004 no longer appeared. For rare earths, these changes are maintained all the way up to a nine year time period, and the only reason why is it not so in 10 is because there was not enough data to calculate 1999. A period of six years, however, provides that data with as little detail lost and as few calculations missed due to lack of data as possible, see Table 8.

Material	Determined Years	Original IST, 5 years	Original IST, 6 Years
Palladium	1999-2001	1999-2006	1998-2007
Tungsten	2004-Present	1999-2002, 2004-2009, 2011-2013	1999-2013
Tantalum	2000-2001	2000-2005	2000-2006
Tin	2007-2010	2007*	2007
Nickel	2006-2008		
Tellurium	2008-2011	2008*	
Rare Earths	2010-2012	2006-2013	2001-2013
Before Determined Years	After Determined Years or Not at All	Matching Determined Years	*Very Close to Threshold

Table 9: Summary of Calculations

Overall, what is shown is that both raising and lowering the time period have their benefits. When the time period is lowered, it is much easier to view the year to year details that are lost when the time period is expanded. When the time period is increased, the small events that aren't overly important can be balanced out so that a more general trend may be formed. From what we observed, and can be seen in Table 9, raising the time period to six years was the most beneficial when looking at the materials we chose with market anomalies. The IST tended to detect potential criticality earlier, and covered up smaller gaps that would have confused reports.

It should be briefly mentioned, once more, that the threshold value of 0.335 would not be the correct value to use, as it would change with the C values.

4.3 Other Improvements

Over the course of our project, we researched many materials, not all of which ended up on our list of seven cases of material market anomalies. Nonetheless, the research process helped identify opportunities where including some additional functionality in the tool could be useful for analyses related to material criticality. For example, including contract pricing information, co-production and byproduct information, and expansion of materials included in the tool would all be beneficial upgrades. The price of manganese is closely related to the price of manganese alloy production through the use of contract pricing. Having information in the tool on contract pricing as an indicator or as some visual aid would allow for easier analysis of materials that have contract pricing. After studying bauxite and aluminum, we realized that since bauxite was a precursor to aluminum, both materials would be linked. In the current state, the tool does not have information on materials that are precursors of other materials, or are by-products of the production of other materials.

5. Recommendations

Our recommendations fall under three categories. The first are possible improvements to the methodology of the tool, or more specifically, reexaminations of how the final value of C is calculated. The second are possible interface improvements, and the third are expansions to the scope of the model. The third are expansions to the scope of the model

5.1: Methodological Improvements

Consider of alternative relative weights for sub-indicators. In most of the cases we examined, the value of M suppresses the overall criticality until some material anomaly actually occurs, which is not helpful. In an attempt to fix this, we tried three alternative weighting structures that increased the impact of I and reduced the impact of M. An overall increase in potential criticality values was observed, which in turn leads to earlier detection of potential criticality. Of course, if this method was actually chosen, more than two set of weights would need to be tested against all of the materials in the tool.

Consider methodological modifications that take into account the tool's sensitivity to the time period over which production growth and price volatility are calculated. The period of time over which sub-indicators I and M are calculated is five years. Through our work, we raised and lowered the time period in an attempt to see its effect on the final criticality values (see Appendix E). We even found what happens when we vary what time period is used between I and M, seeing if there was some unequal combination that allowed C to be more accurate in detecting material anomalies (see Appendix F). We looked for time periods that notice the year of material market anomaly earlier and time periods that covers any single year gaps between periods of potential criticality. For these purposes, we found that a time period of six years worked quite well. However, this change did not have a universal effect on all the materials studied. Furthermore, this time period may not work for the rest of the materials in the tool.

5.2: Interface Improvements

We recommend that the colors for each country in the graph of production and price be standardized. Currently, the changing colors on indicator graphs makes comparison between multiple materials confusing. Each country having a standard color allows for easier comparison between the materials. Since this tool is intended to be used by the general public, the interface should be as streamlined as possible and be consistent in its coloring in order to increase the ease of use.

We recommend that the colors for the indicators for the graph of single commodities time series and indicator tables are consistent for each material. Currently, the value of an indicator can be the same for two materials but be represented as two different colors. The difference in colors make it harder to quickly understand if a material is flagged as potentially critical in a given year or compare values across materials. Changing all the colors to have the same color scale would fix this issue.

5.3: Tool Expansion

Consider expanding the IST to include links between materials. Including the links between materials like bauxite and aluminum would expand knowledge relating to the possible causes of potential material criticality. This could be accomplished by combining the graphs of the two materials, or just including a note on each material showing that it is linked to another material. Relationships between materials may not be clear and require more research, so the model having these relationships would save time and resources of agencies who may use the model. Other relationships that would need to be noted would be co-production, where materials are mined together and then extracted through a shared process, and by-products, where the mining, refining, and or processing methods of a primary material result in another secondary material being produced as well. It would be very useful to have a visualized form of these precursor, co-production, and by-production relationships in the tool. In addition, a connection within the tool between a material and its precursors would allow for easy cross reference between them and, therefore, reduce effort for finding cause-and-effect events.

We suggest that the scope of the tool be expanded to include other materials such as isotopes, gases, and other chemical compounds. Information on isotopes and key chemical compounds would allow their respective industries and agencies to able to detect any potential criticality. An example of this is molybdenum-99m, an isotope of molybdenum that decays into technetium-99, which is prominently used in medical imaging technology. Other materials that it would beneficial to track, indium tin oxide, sawdust, cement, nitrocellulose, rosin, acrylic acid, carbon black, titanium dioxide, plutonium, rubber, and nylon. All of these materials were identified in our search of new sources, but do not appear in the tool.

Consider adding contract pricing information to the tool. Another important factor we noticed was the lack of data on materials sold through annual contracts. The unique part about contract-based materials is that their price does not react in accordance with demand because the price is set. If a material is mainly sold through contract, then the data for its pricing may no longer be accurate. Therefore, including some indication as to whether or not a material is sold mainly via contract in order to give insight on their potential criticality.

5.4: Future Analysis Possibilities

Consider the reporting results in the form of a ranked list that compares relative criticality values. The threshold value of 0.335 is arbitrary and does not reflect how criticality is a subjective concept. An idea we had come up with to fix this would be to report a chart that compared the potential criticality values, and even their sub indicators, creating a ranked list of the materials. These would remove the values from being the primary deliverable, which have the chance of easily confusing those who do not fully understand what they were looking at. The ranked list would also move focus to changes of ordering year to year. More importantly, organizations and agencies could easily see how each material relevant to their interests compared to others.

Consider creating additional sub-indicators. This suggestion would require further analysis, as what factors may be helpful additions seem to vary from material to material. Some analysis of what potential factors would be beneficial to the most materials would be vital. From our research we found several examples to use as a starting point of that analysis. First and foremost, an indicator of substitutability. A material that is vital but easily substituted is not as critical as one that has no substitutes. An example of a material that has no substitutes would be tungsten. As said previously, there are no materials that have similar properties to tungsten that are capable of withstanding the same temperatures tungsten can. Another possible indicator would be a measure of price elasticity of production. At the moment there is a measure of price volatility, but this factor doesn't take into consideration how production responds to that volatility, which could be a good indicator of delays in the supply chain's response to market signals.

Consider creating a threshold for each individual sub-indicator. We noticed throughout our research that some sub-indicators sent signals of potential criticality before the overall C indicators did. Therefore, it might be worth considering setting a threshold for the sub-indicators. For many materials that don't pass the threshold in criticality, one or more of their sub-indicators are quite high during and before periods of supply anomaly. If a threshold point was set for the sub-indicators as well as the criticality value, it is possible that the methodology need not be changed to the same extent, as materials missed because of their criticality value may still be looked into because of one of their sub-indicators.

6. Conclusions

We examined many factors about how the Interagency Screening Tool determines potential criticality as well as what factors it has missed. We went about this by locating materials that were included in the tool, but had interesting and unique problems. This does a good job to make sure that the tool catches all fringe cases, but it does nothing to ensure that there are no false positives. False positives are actually a lot better than the tool missing potential cases of criticality because the tool is meant to be an early warning. Overall, we think that this is the best strategy because it reduces missed cases, even though it will take more time to work through the extra cases.

Ideally, we would be able to test all of the materials, including those which were actually caught by the tool. This would provide a complete and thorough validation of the tool. By only examining seven materials, we may have over fit our recommendations or missed some cases, but we chose the most unique and varied cases that we were capable of completing in our time frame of seven weeks. Therefore, a good course for further research to take would be to test a wider range of materials against the tool and see if they come to similar conclusions as we did.

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Appendix A: Worldwide Governance Indicators

The worldwide indicators were developed by the World Bank to categorize and analyze multiple countries. It measures the quality of governance in multiple countries from over 40 data sources updated every year since 2002. The result of this study by the World Bank is the worldwide indicators.

The worldwide indicators range over multiple factors. Voice and Accountability "reflects perceptions of the extent to which a country's citizens are able to participate in selecting their government, as well as freedom of expression, freedom of association, and a free media"(Kaufmann D. et al. 2010). Political Stability and Absence of Violence/Terrorism "reflects perceptions of the likelihood that the government will be destabilized or overthrown by unconstitutional or violent means, including politically-motivated violence and terrorism"(Kaufmann D. et al. 2010). Government Effectiveness "reflects perceptions of the quality of public services, the quality of the civil service and the degree of its independence from political pressures, the quality of policy formulation and implementation, and the credibility of the government's commitment to such policies"(Kaufmann D. et al. 2010). Regulatory Quality "reflects perceptions of the ability of the government to formulate and implement sound policies and regulations that permit and promote private sector development"(Kaufmann D. et al. 2010). Rule of Law "reflects perceptions of the extent to which agents have confidence in and abide by the rules of society, and in particular the quality of contract enforcement, property rights, the police, and the courts, as well as the likelihood of crime and violence"(Kaufmann D. et al. 2010). Control of Corruption "reflects perceptions of the extent to which public power is exercised for private gain, including both petty and grand forms of corruption, as well as ''capture'' of the state by elites and private interests"(Kaufmann D. et al. 2010).

Appendix B: Chart of Agency Specific Criticality

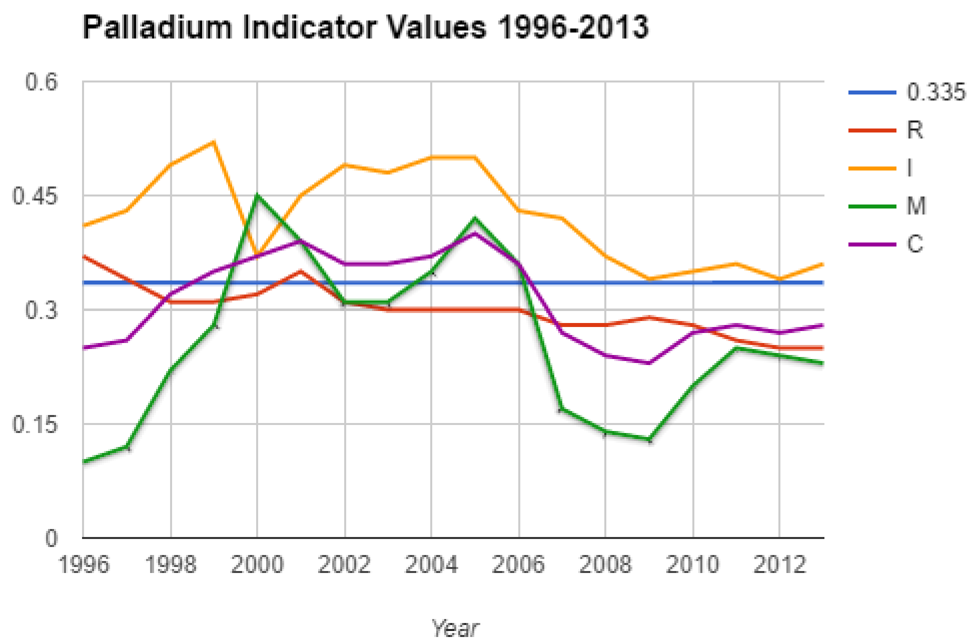
From 2016 GAO Report

Table 5: Results of Selected Critical Materials Assessments for U.S. Economic and National Security Interests

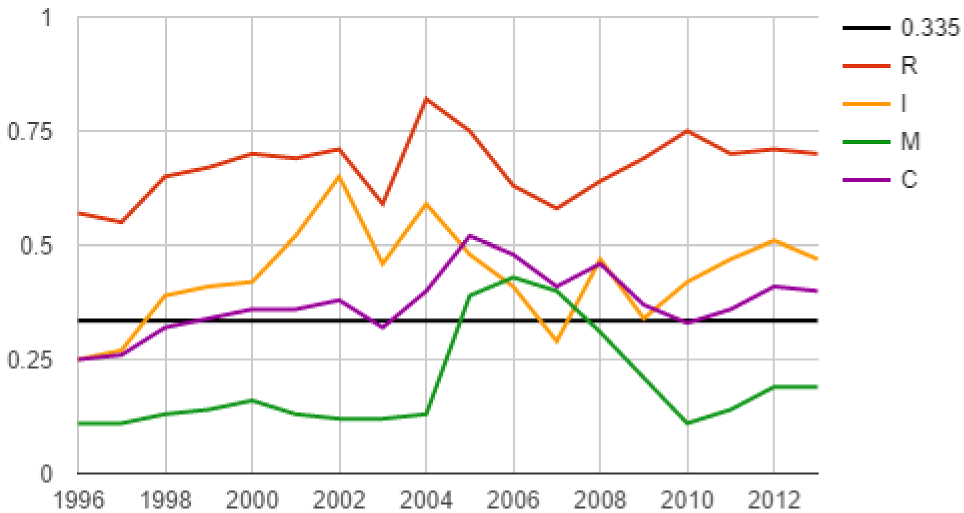
Materials identified as critical or potentially critical	National Academies of Sciences, Engineering, and Medicine (2008)[a]	Department of Energy (2010)[b]	Department of Energy (2011)[c]	Department of Defense (2015)[d]	National Science and Technology Council Subcommittee on Critical and Strategic Mineral Supply Chains (2016)[e]
Rare earth elements					
Cerium	x				x
Dysprosium	x	x	x		x
Erbium	x				x
Europium	x	x	x	x	x
Gadolinium	x				x
Holmium	x				x
Lanthanum	x			x	x
Lutetium	x				x
Neodymium	x	x	x		x
Praseodymium	x				x
Promethium	x				x
Samarium	x				x
Scandium	x				
Terbium	x	x	x		x
Thulium	x				x
Ytterbium	x				x
Yttrium	x	x	x		x
Platinum group metals					
Iridium	x				x
Osmium	x				
Palladium	x				
Platinum	x				
Rhodium	x				x
Ruthenium	x				x
Other materials					
Aluminum oxide, fused crude				x	
Antimony				x	x

Materials identified as critical or potentially critical	National Academies of Sciences, Engineering, and Medicine (2008)[a]	Department of Energy (2010)[b]	Department of Energy (2011)[c]	Department of Defense (2015)[d]	National Science and Technology Council Subcommittee on Critical and Strategic Mineral Supply Chains (2016)[e]
Beryllium				x	
Bismuth mine production					x
Boron carbide				x	
Carbon fiber (seven types)				x	
Chlorosulfonated polyethylene				x	
Cobalt mine production					x
Indium	x	x			
Ferromolybdenum					x
Germanium				x	x
Magnesite					x
Magnesium				x	
Manganese	x			x	
Mercury					x
Mica					x
Monazite					x
Niobium	x				
Silicomanganese					x
Silicon carbide fiber, multifilament				x	
Tungsten				x	x
Tungsten-rhenium alloy				x	
Vanadium					x
Yttrium oxide				x	

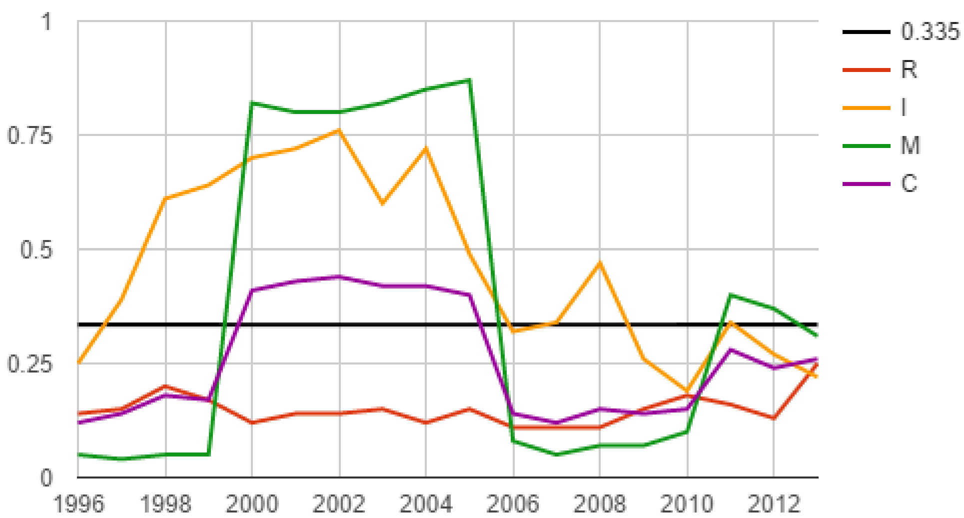
Appendix C: Indicator Values by Material, 1996-2013

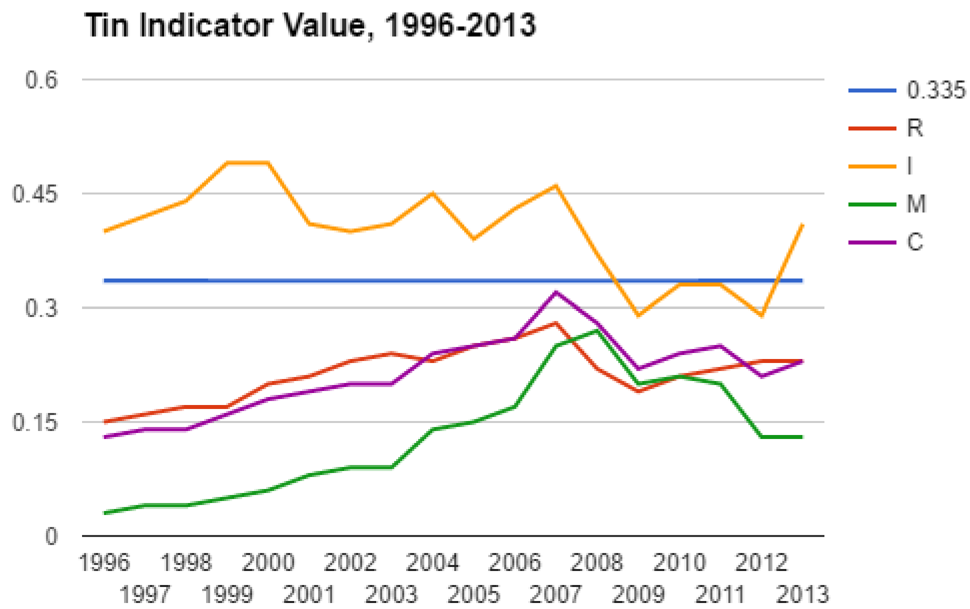


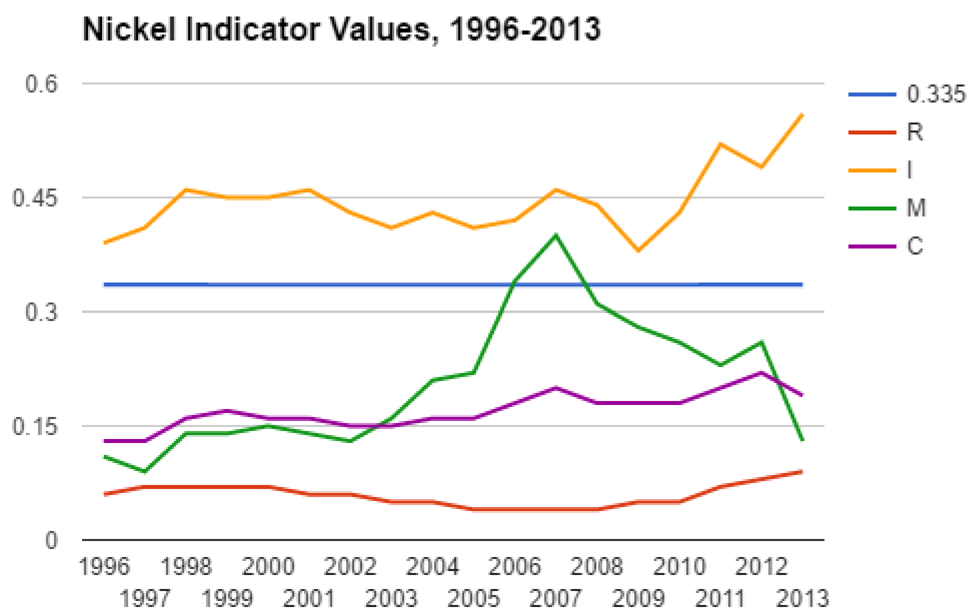
Tungsten Indicator Values 1996-2013

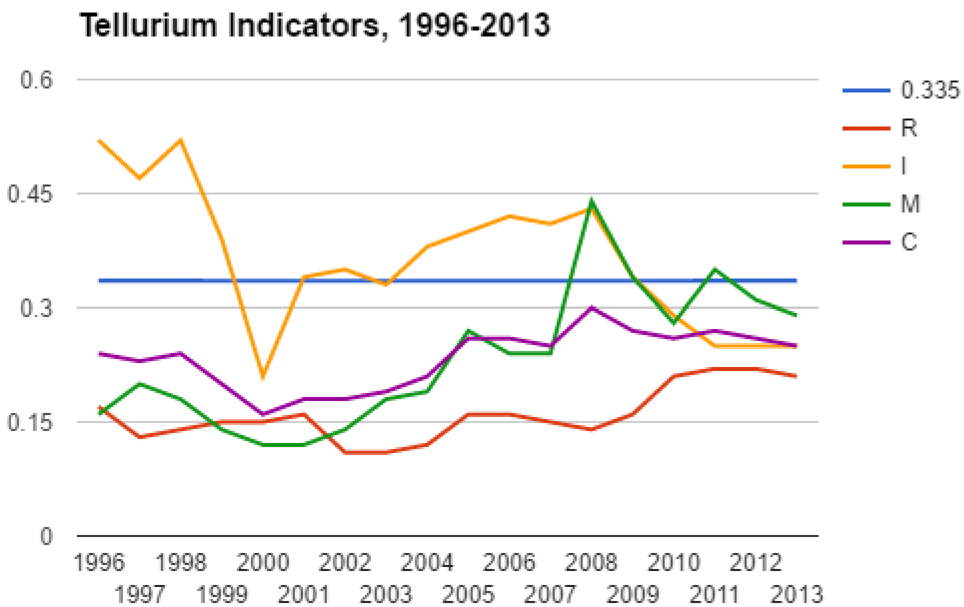


Tantalum Indicator Values 1996-2013

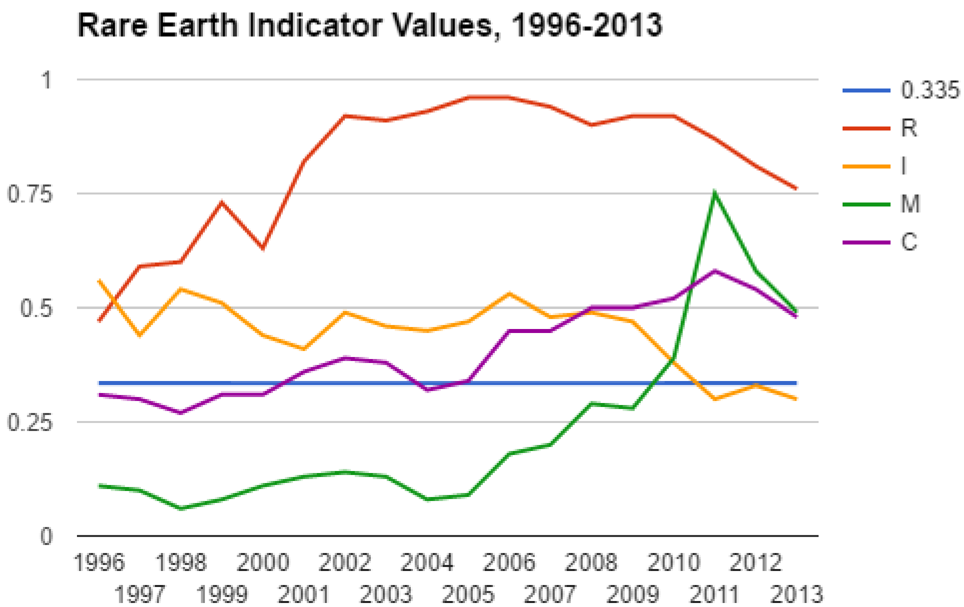



Tin Indicator Value, 1996-2013
0.6
0.45
0.3
0.15
0
1996 1998 2000 2002 2004 2006 2008 2010 2012
1997 1999 2001 2003 2005 2007 2009 2011 2013
0.335
R
I
M
C

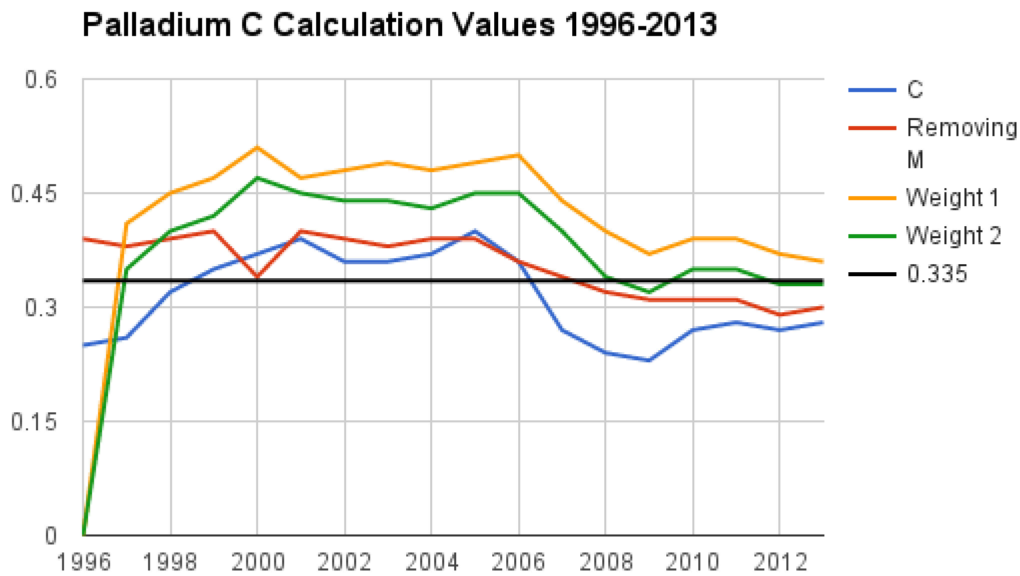

Nickel Indicator Values, 1996-2013
0.6
0.45
0.3
0.15
0
1996 1998 2000 2002 2004 2006 2008 2010 2012
1997 1999 2001 2003 2005 2007 2009 2011 2013
0.335
R
I
M
C



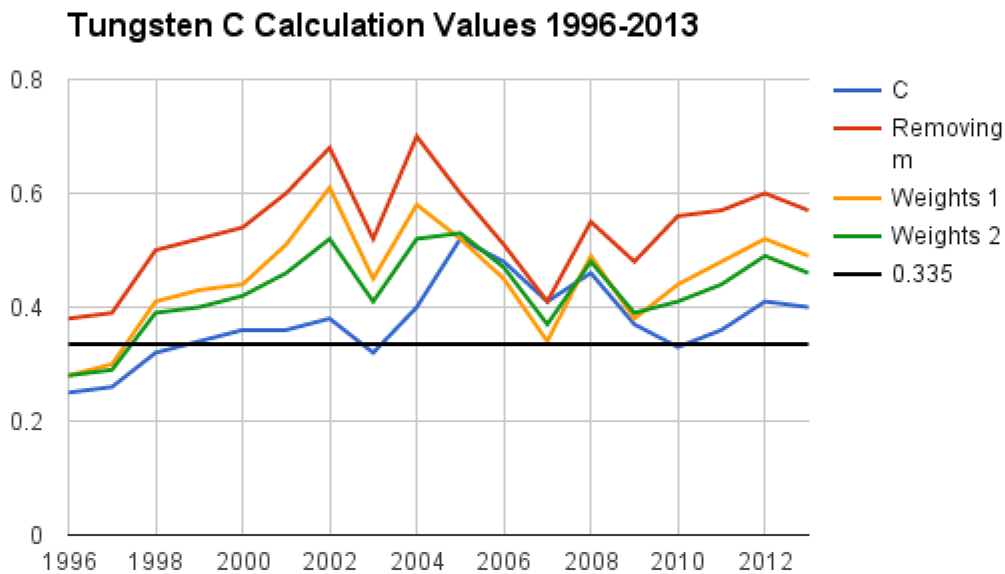
Tellurium Indicators, 1996-2013
0.6
0.45
0.3
0.15
0
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
0.335
R
I
M
C


Rare Earth Indicator Values, 1996-2013
1
0.75
0.5
0.25
0
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
0.335
R
I
M
C

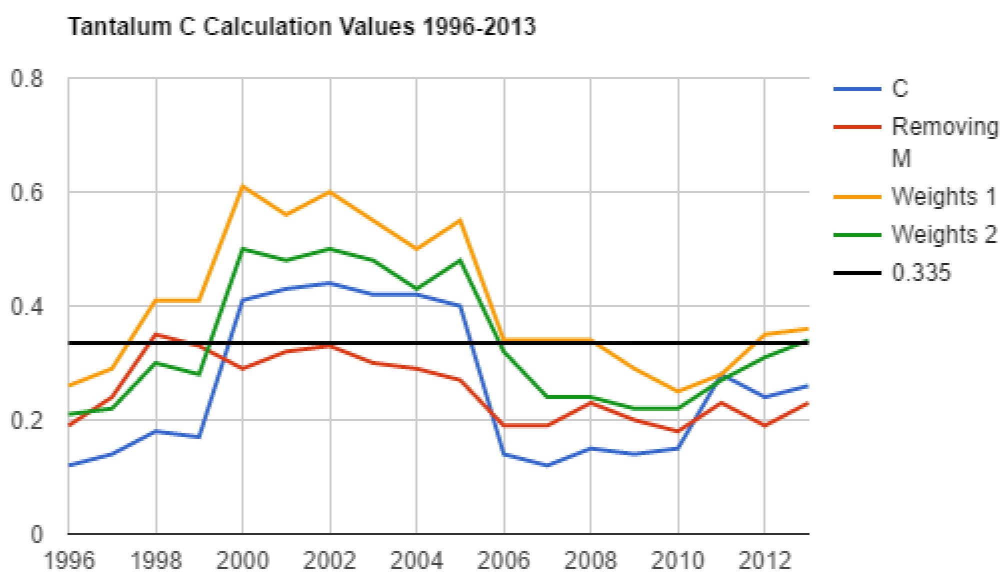
Appendix D: Alternative C Calculations by Material



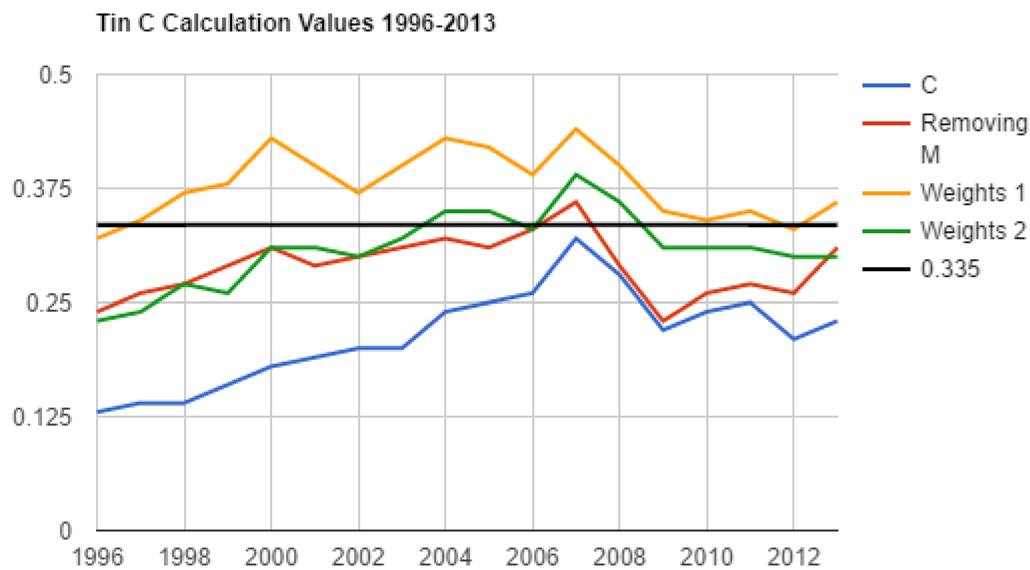
(NSTC 2016)

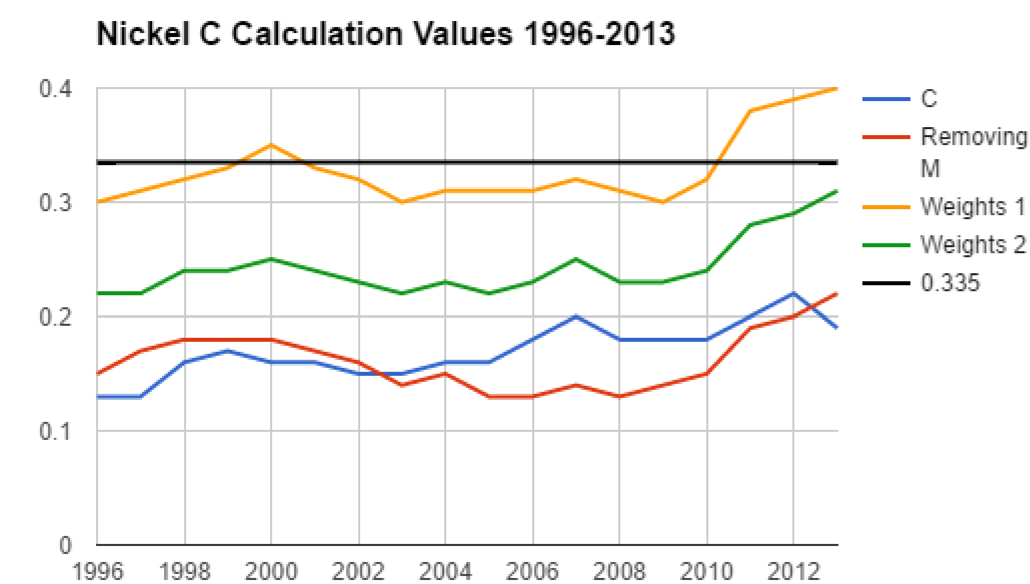


(NSTC 2016)

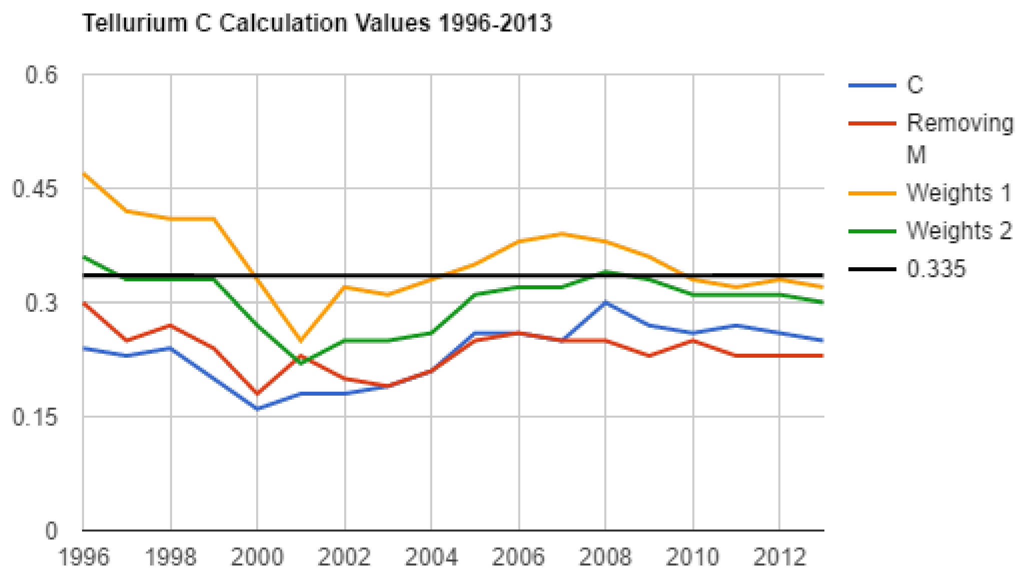


(NSTC 2016)

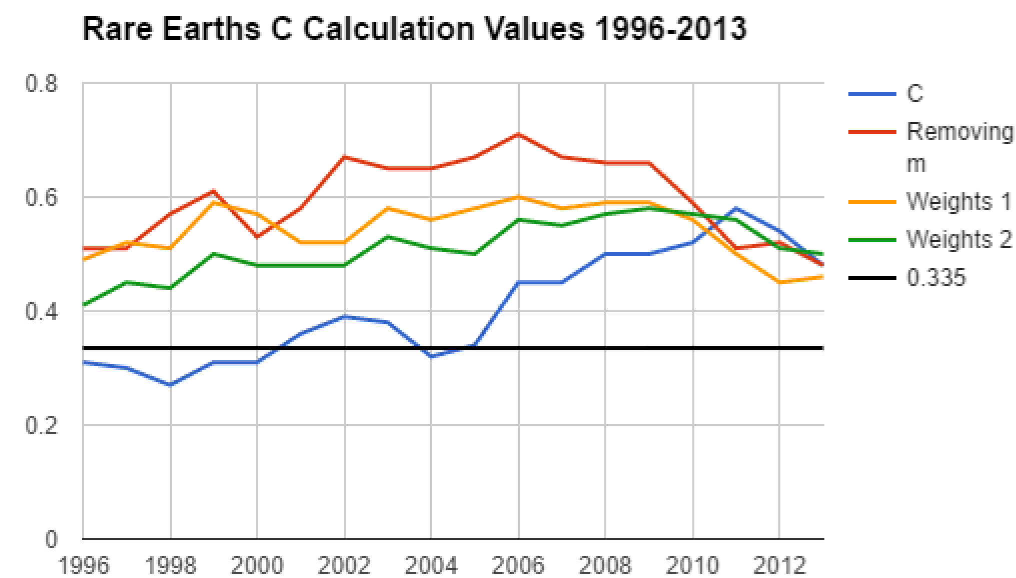

Tin C Calculation Values 1996-2013
0.5
0.375
0.25
0.125
0
1996
1998
2000
2002
2004
2006
2008
2010
2012
C
Removing M
Weights 1
Weights 2
0.335


Nickel C Calculation Values 1996-2013
0.4
0.3
0.2
0.1
0
1996
1998
2000
2002
2004
2006
2008
2010
2012
C
Removing M
Weights 1
Weights 2
0.335

(NSTC 2016)

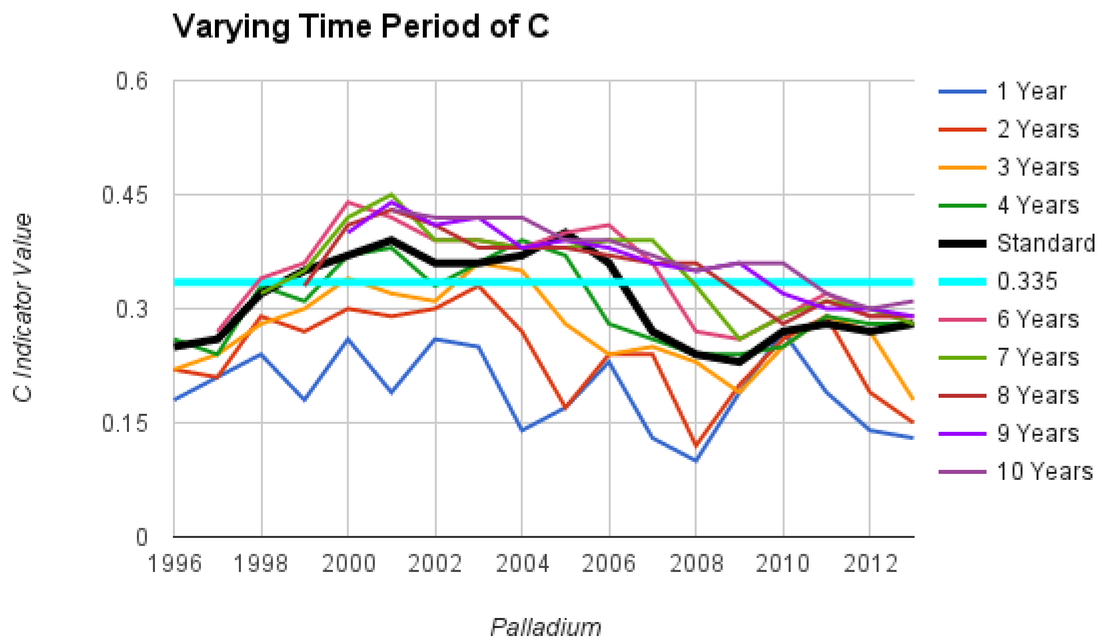


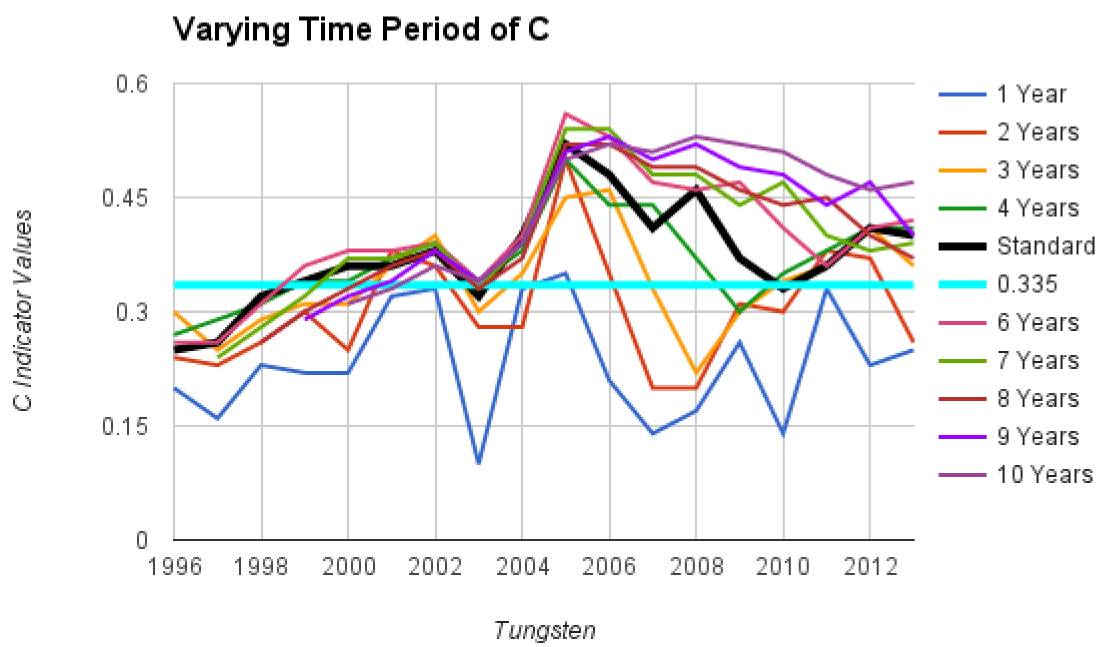
(NSTC 2016)

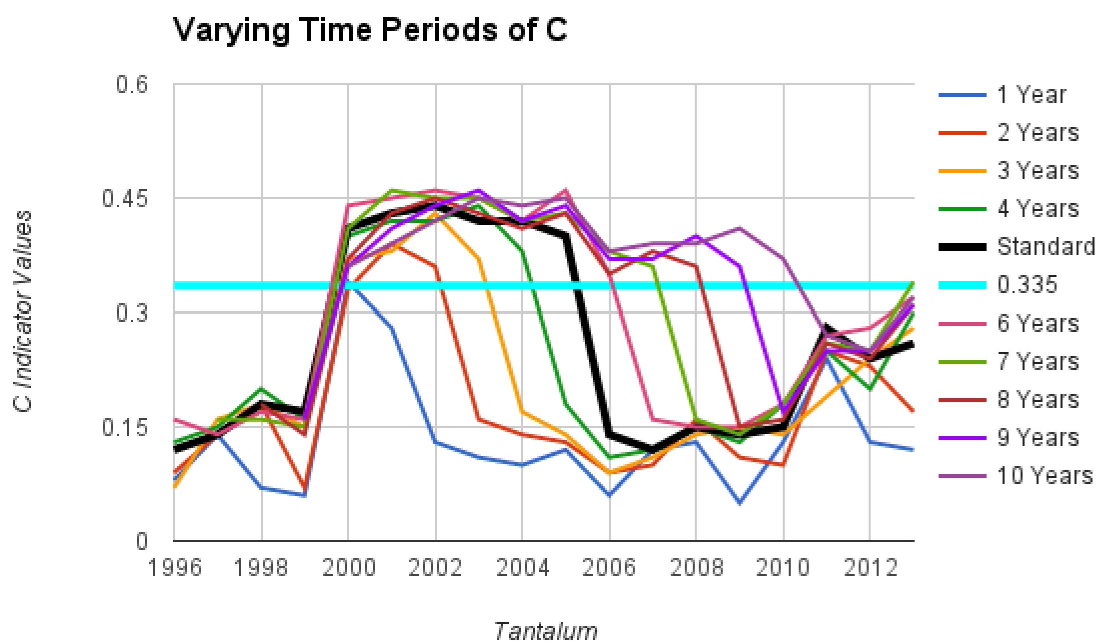


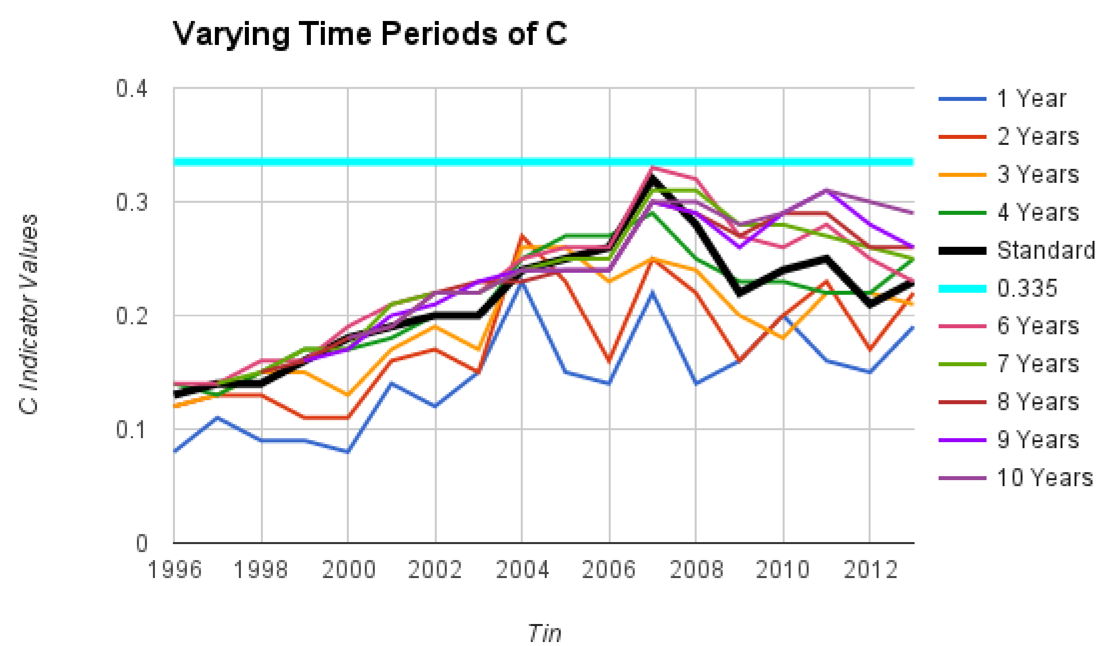
(NSTC 2016)

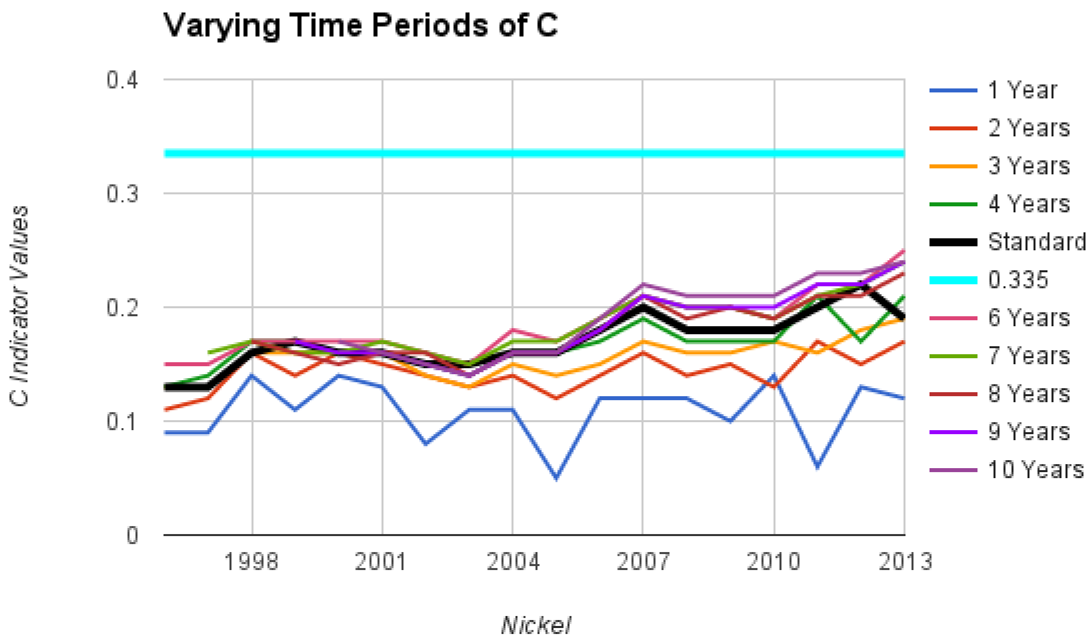
Appendix F: Charts of C by Material, with Varying Time

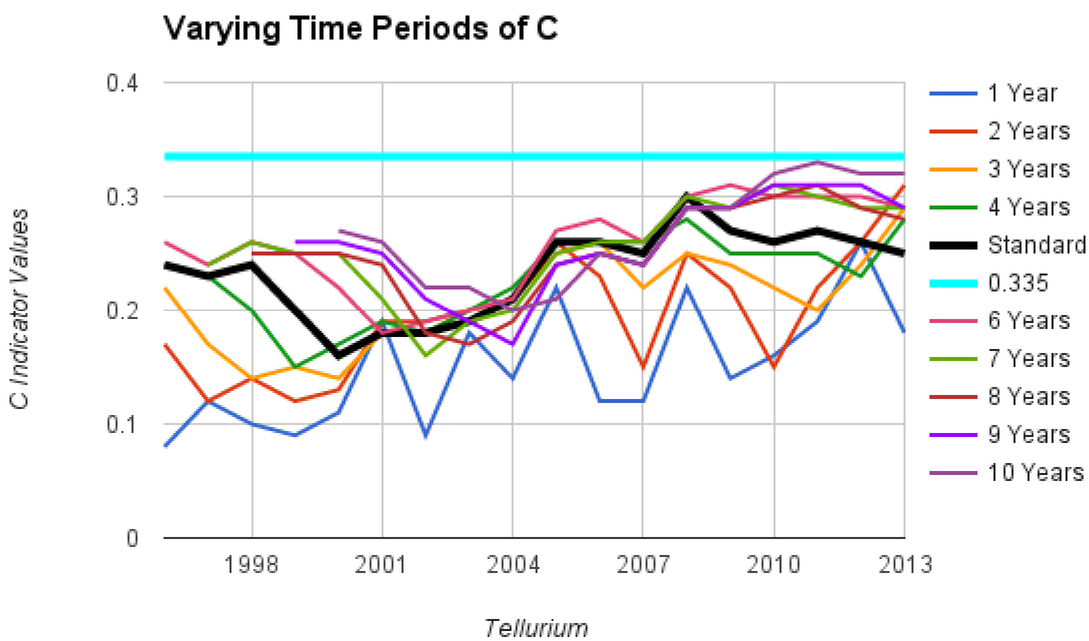


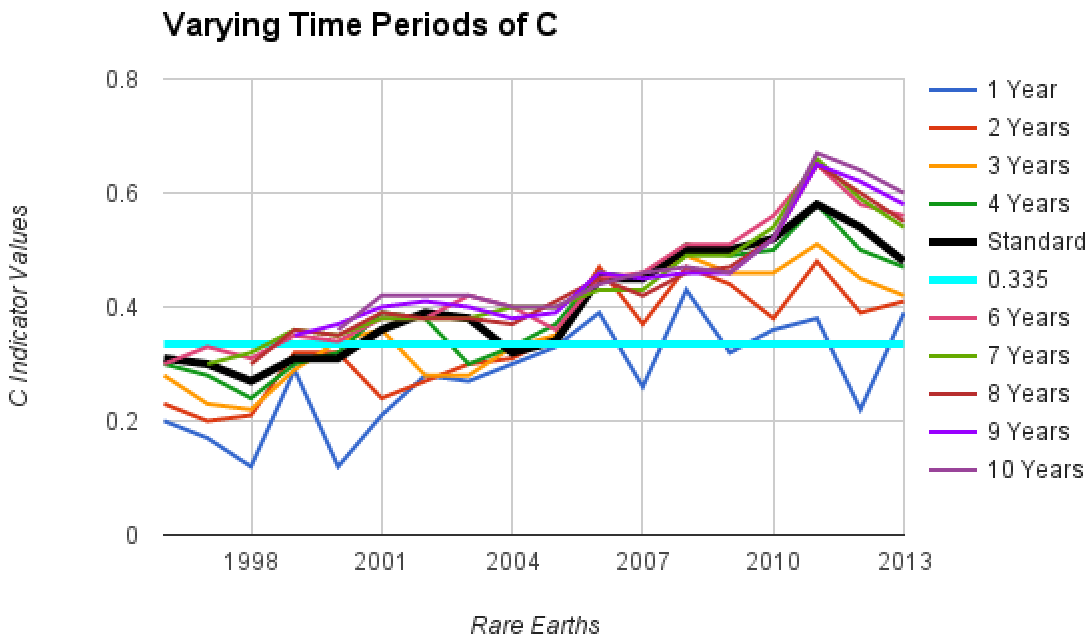



Varying Time Periods of C
0.6
0.45
0.3
0.15
0
C Indicator Values
1996
1998
2000
2002
2004
2006
2008
2010
2012
Tantalum
1 Year
2 Years
3 Years
4 Years
Standard
0.335
6 Years
7 Years
8 Years
9 Years
10 Years

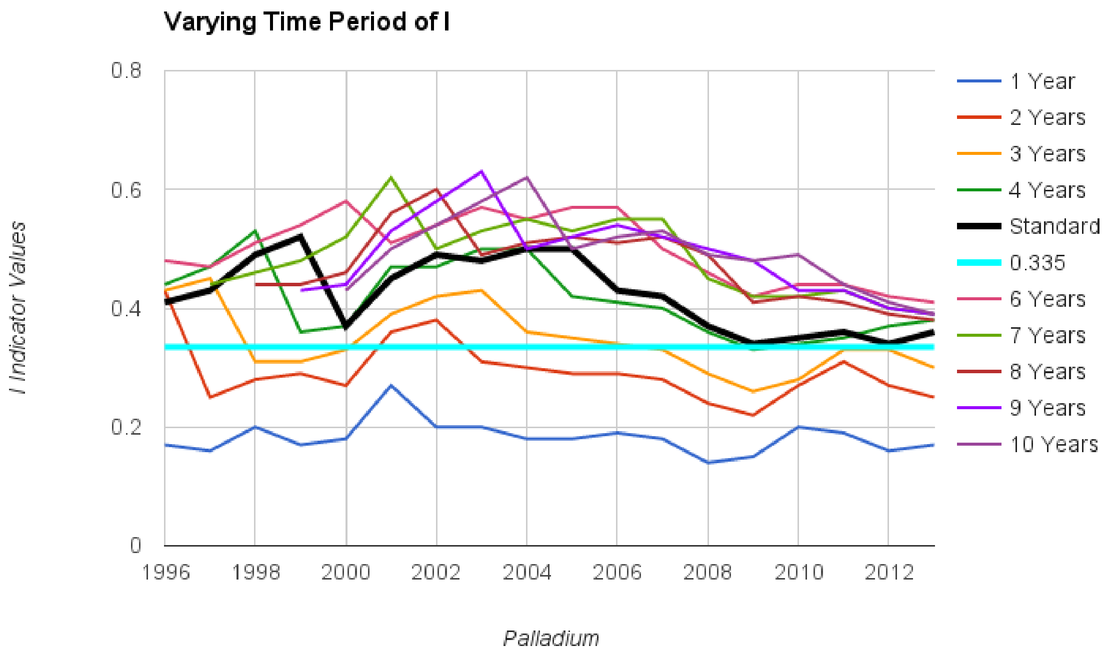

Varying Time Periods of C
0.4
0.3
0.2
0.1
0
C Indicator Values
1996
1998
2000
2002
2004
2006
2008
2010
2012
Tin
1 Year
2 Years
3 Years
4 Years
Standard
0.335
6 Years
7 Years
8 Years
9 Years
10 Years

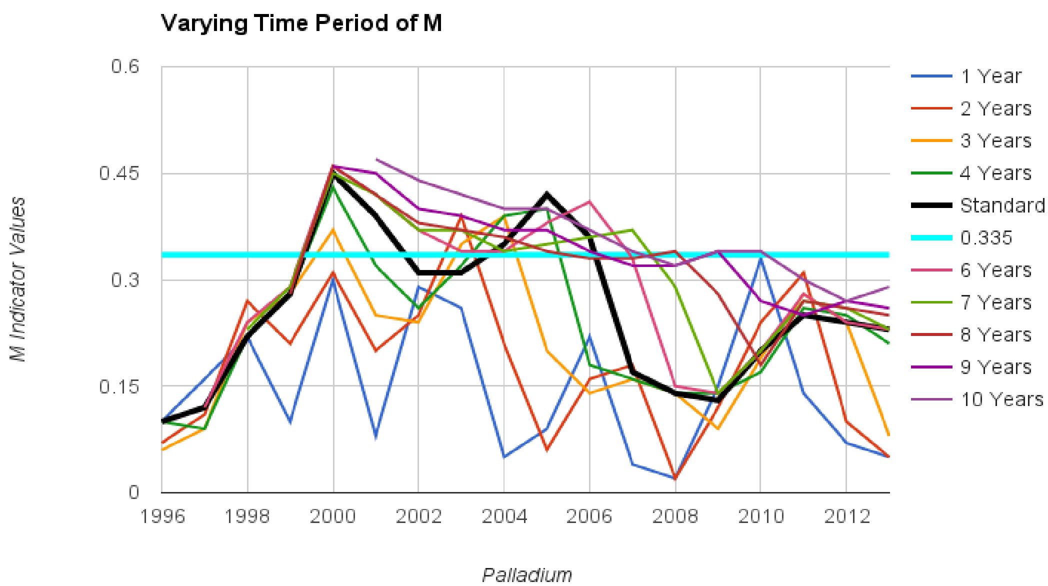

Varying Time Periods of C
C Indicator Values
0.4
0.3
0.2
0.1
0
1998
2001
2004
2007
2010
2013
Nickel
1 Year
2 Years
3 Years
4 Years
Standard
0.335
6 Years
7 Years
8 Years
9 Years
10 Years

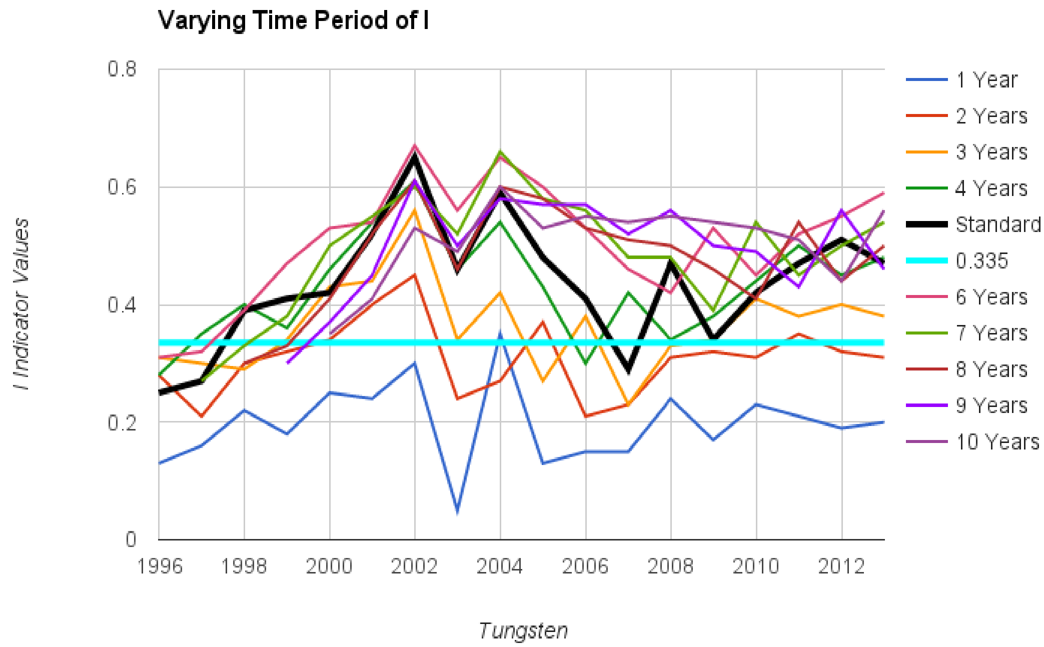

Varying Time Periods of C
C Indicator Values
0.4
0.3
0.2
0.1
0
1998
2001
2004
2007
2010
2013
Tellurium
1 Year
2 Years
3 Years
4 Years
Standard
0.335
6 Years
7 Years
8 Years
9 Years
10 Years

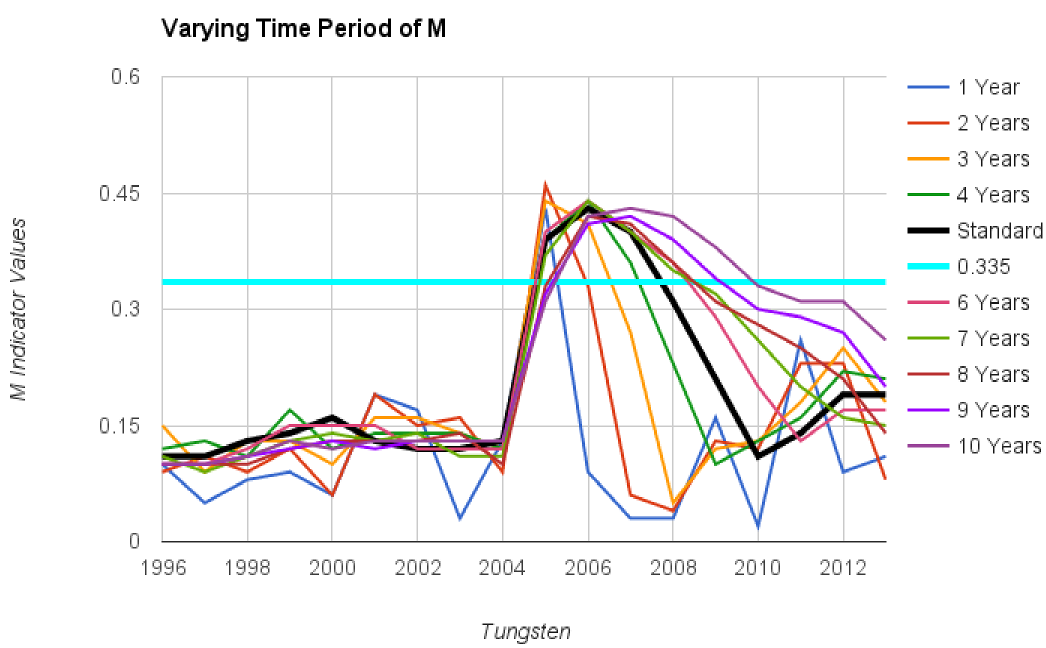

Varying Time Periods of C
0.8
0.6
0.4
0.2
0
C Indicator Values
1998
2001
2004
2007
2010
2013
Rare Earths
1 Year
2 Years
3 Years
4 Years
Standard
0.335
6 Years
7 Years
8 Years
9 Years
10 Years

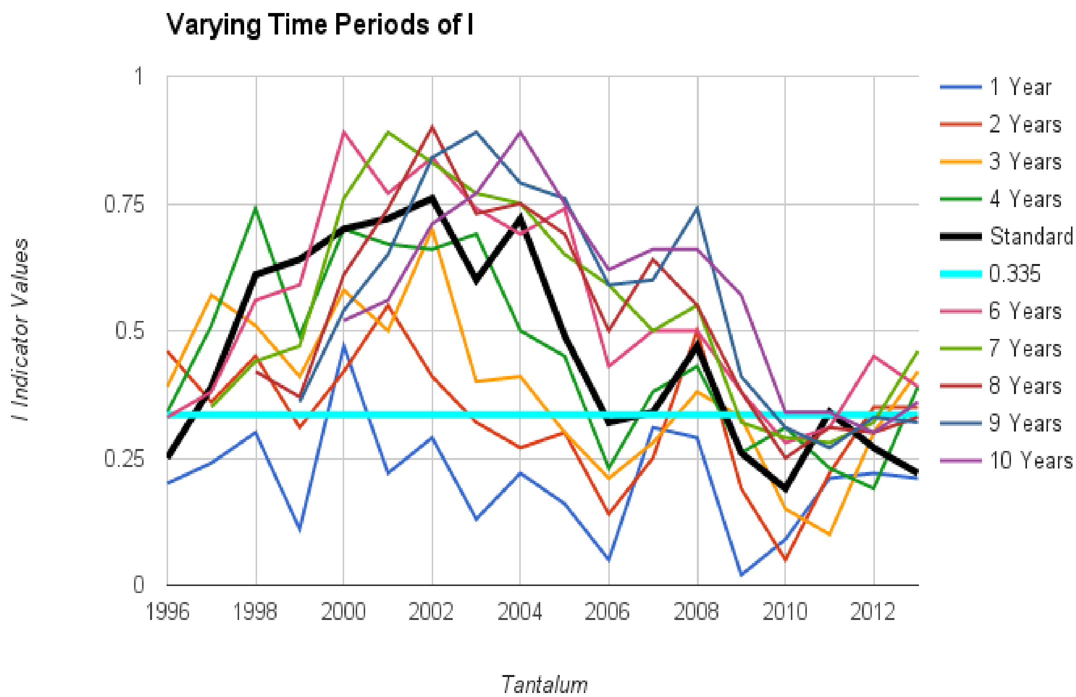
Appendix F: Charts of I and M by Material, with Varying Time Period

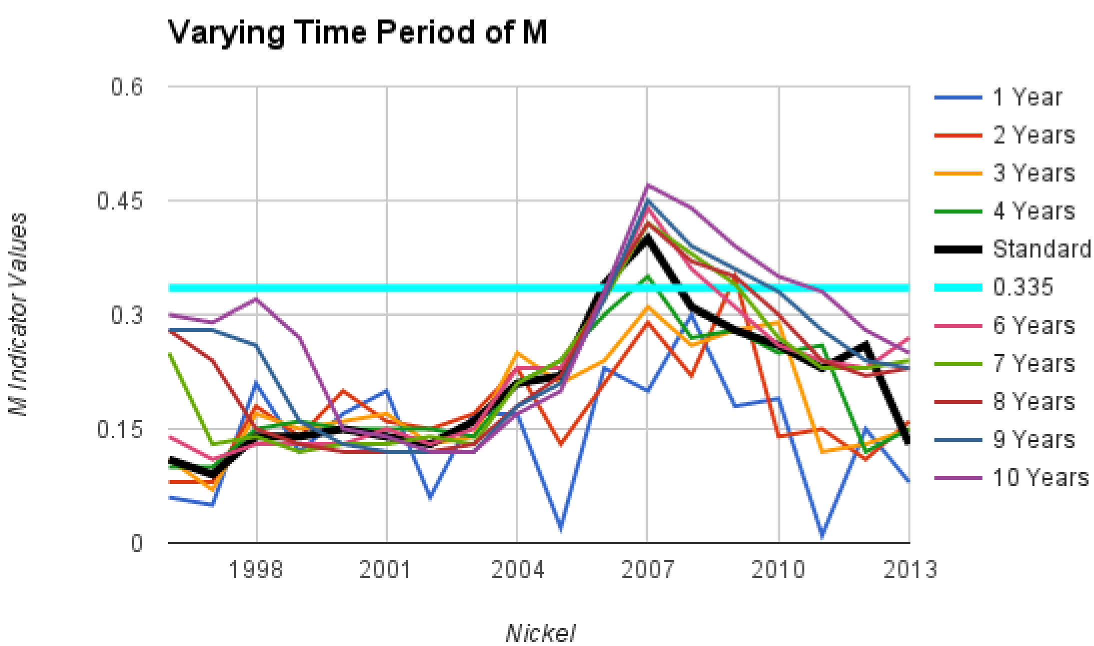


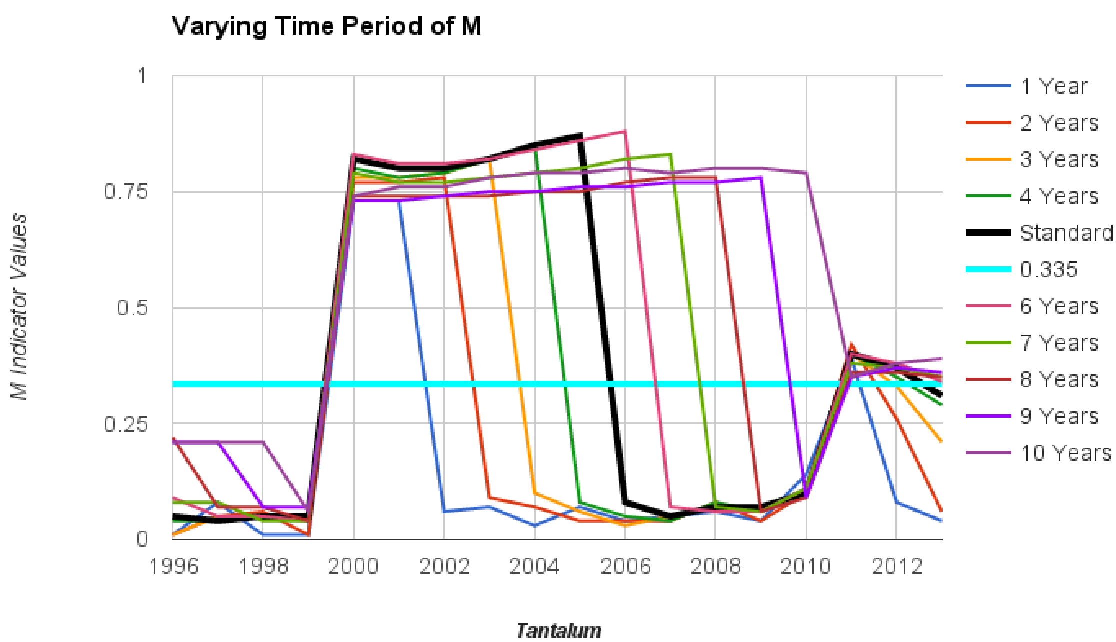



Varying Time Period of I
0.8
0.6
0.4
0.2
0
1996
1998
2000
2002
2004
2006
2008
2010
2012
I Indicator Values
Tungsten
1 Year
2 Years
3 Years
4 Years
Standard
0.335
6 Years
7 Years
8 Years
9 Years
10 Years

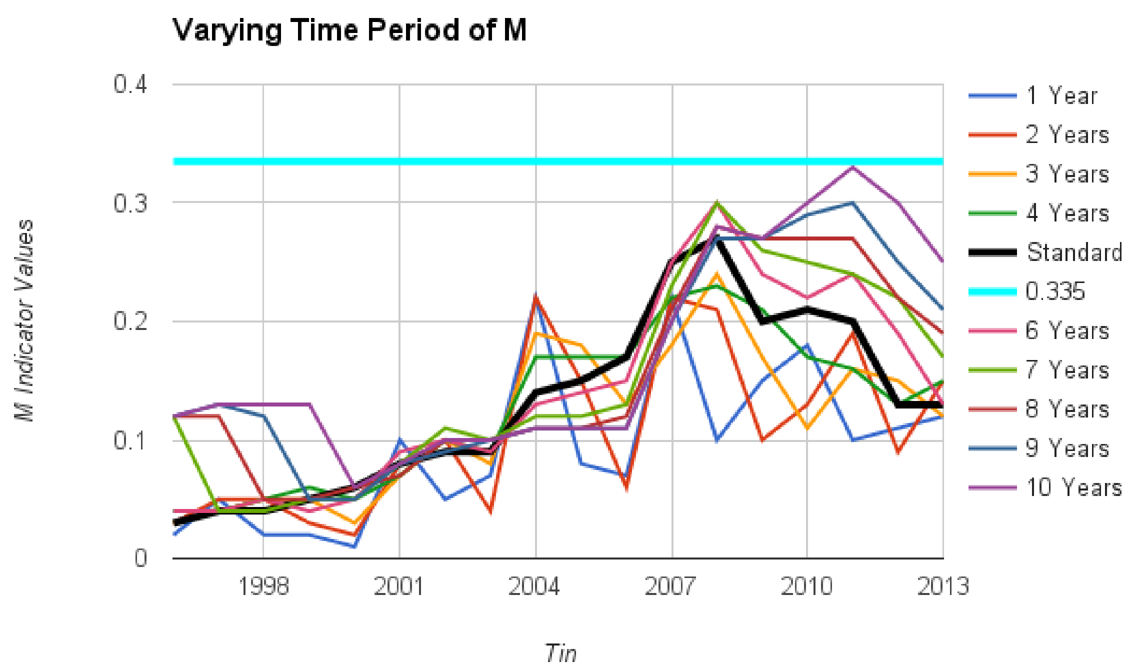

Varying Time Period of M
0.6
0.45
0.3
0.15
0
1996
1998
2000
2002
2004
2006
2008
2010
2012
M Indicator Values
Tungsten
1 Year
2 Years
3 Years
4 Years
Standard
0.335
6 Years
7 Years
8 Years
9 Years
10 Years


Varying Time Periods of I
I Indicator Values
1
0.75
0.5
0.25
0
1996
1998
2000
2002
2004
2006
2008
2010
2012
Tantalum
1 Year
2 Years
3 Years
4 Years
Standard
0.335
6 Years
7 Years
8 Years
9 Years
10 Years

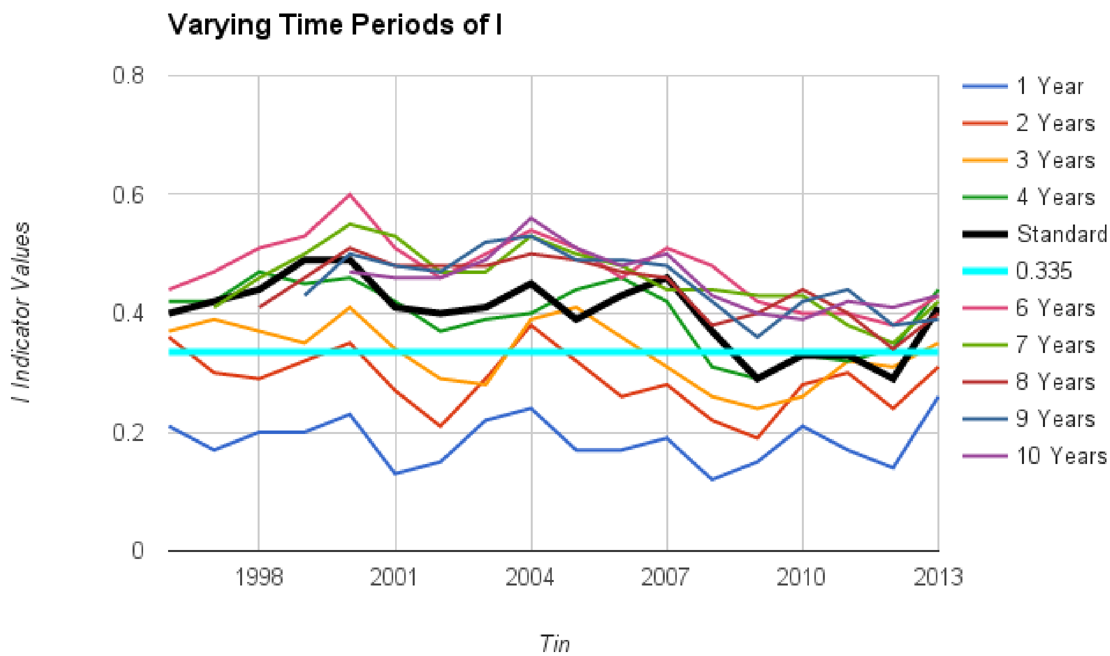

Varying Time Period of M
M Indicator Values
0.6
0.45
0.3
0.15
0
1998
2001
2004
2007
2010
2013
Nickel
1 Year
2 Years
3 Years
4 Years
Standard
0.335
6 Years
7 Years
8 Years
9 Years
10 Years

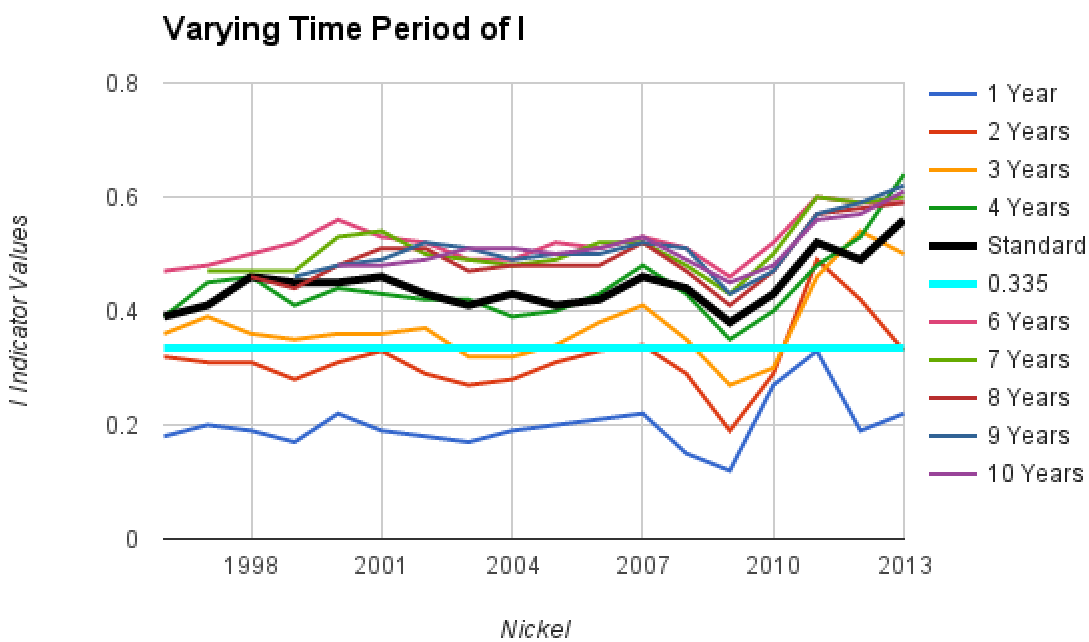


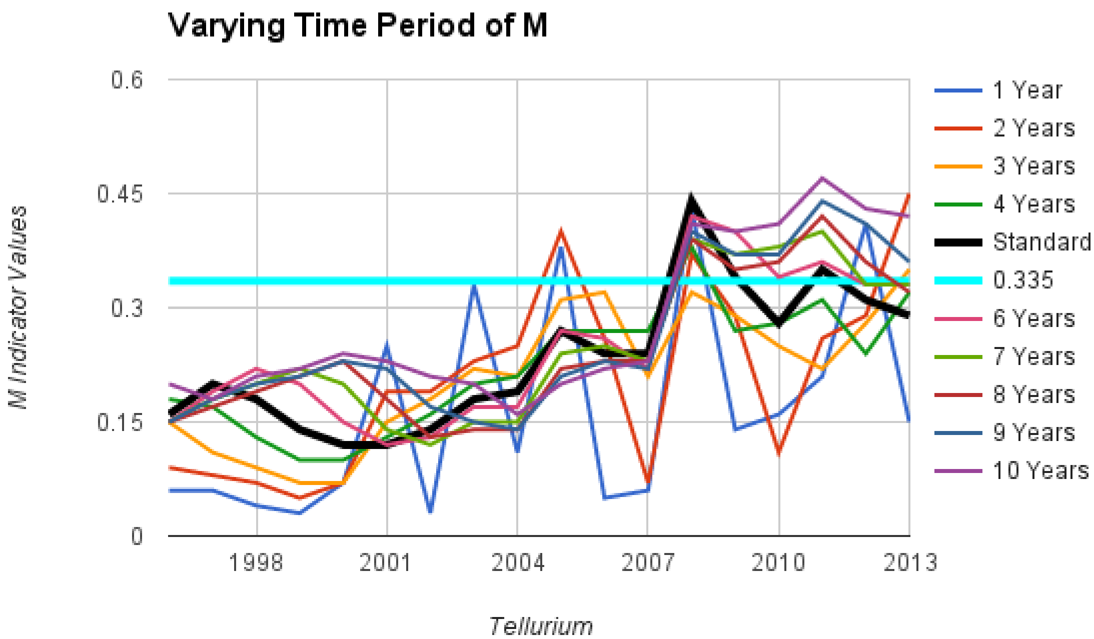
Varying Time Period of M
M Indicator Values
1
0.75
0.5
0.25
0
1996
1998
2000
2002
2004
2006
2008
2010
2012
1 Year
2 Years
3 Years
4 Years
Standard
0.335
6 Years
7 Years
8 Years
9 Years
10 Years
Tantalum

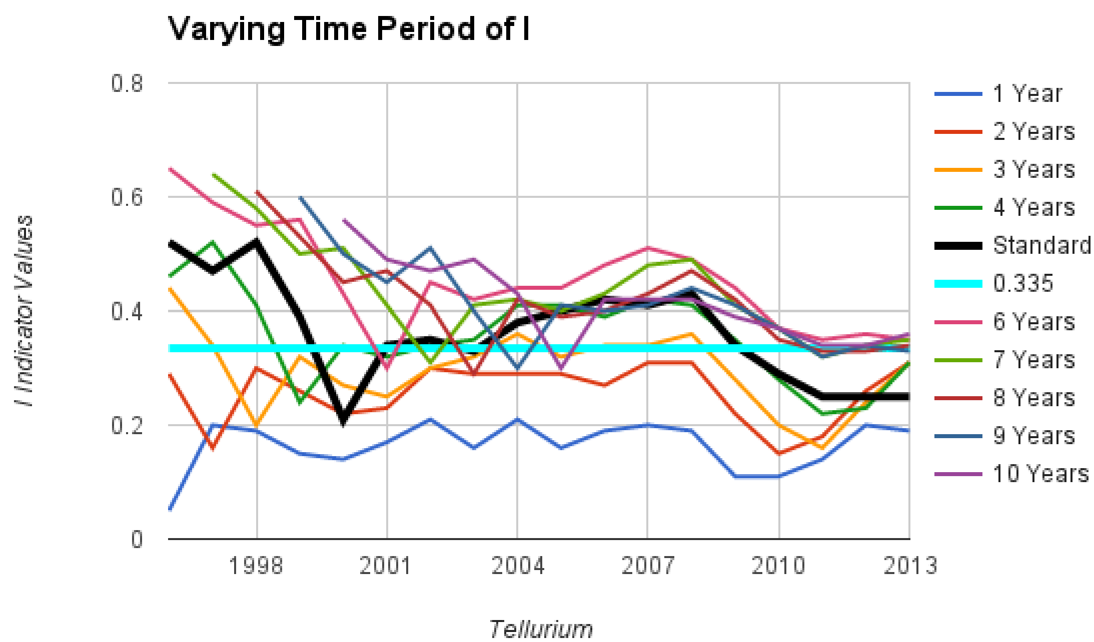


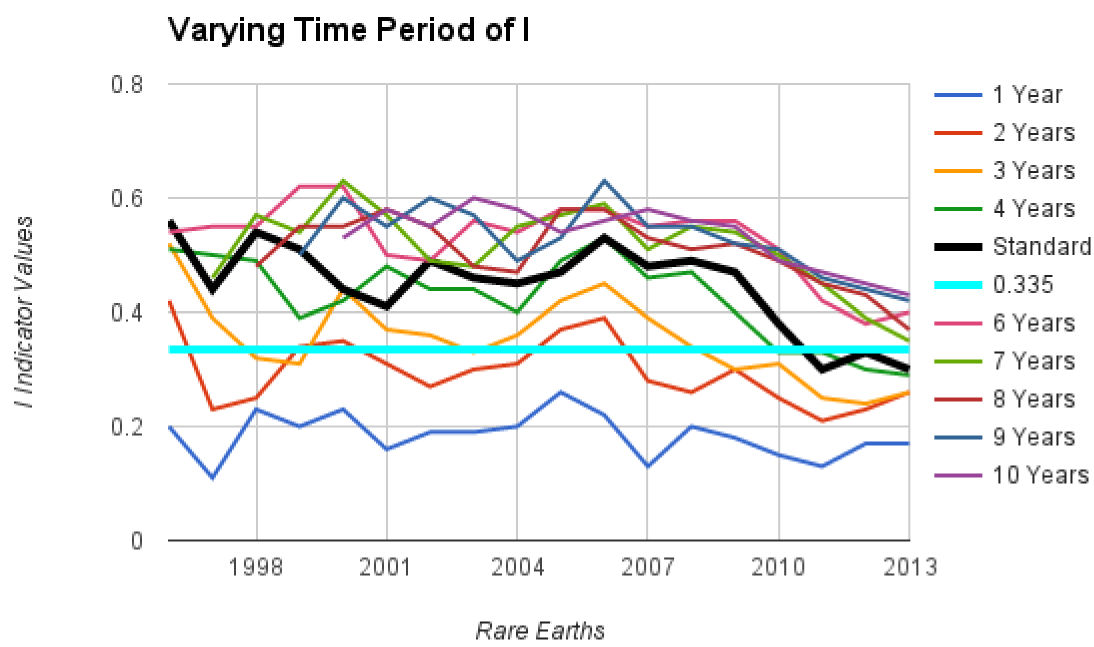
Varying Time Period of M
M Indicator Values
0.4
0.3
0.2
0.1
0
1998
2001
2004
2007
2010
2013
1 Year
2 Years
3 Years
4 Years
Standard
0.335
6 Years
7 Years
8 Years
9 Years
10 Years
Tin

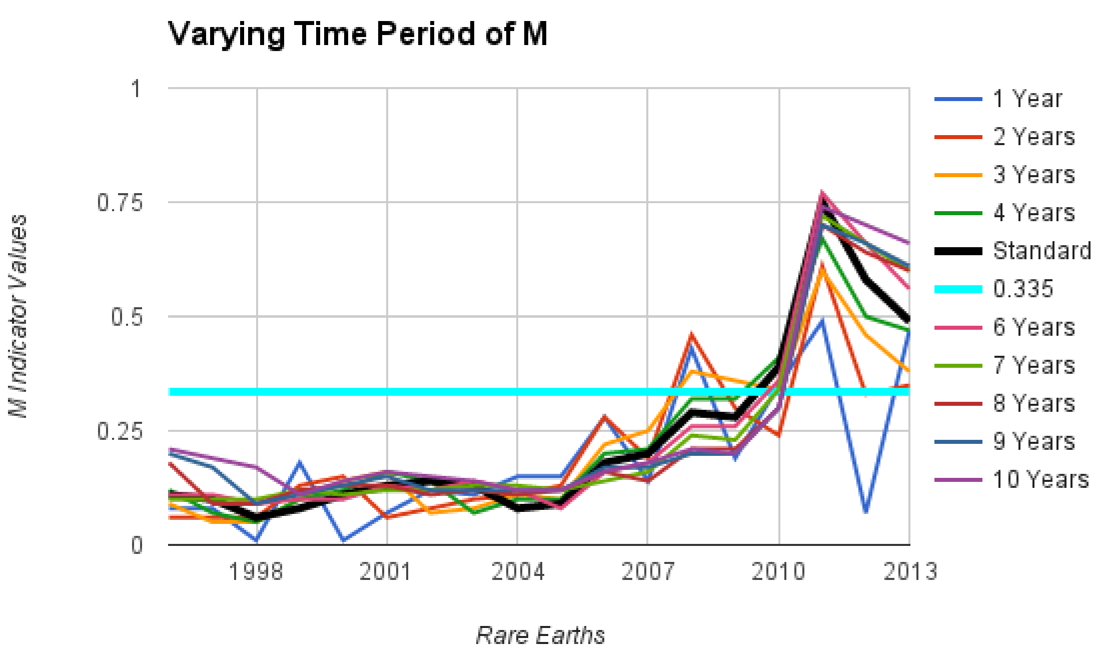

Varying Time Periods of I
0.8
0.6
0.4
0.2
0
I Indicator Values
1998
2001
2004
2007
2010
2013
Tin
1 Year
2 Years
3 Years
4 Years
Standard
0.335
6 Years
7 Years
8 Years
9 Years
10 Years


Varying Time Period of I
0.8
0.6
0.4
0.2
0
I Indicator Values
1998
2001
2004
2007
2010
2013
Nickel
1 Year
2 Years
3 Years
4 Years
Standard
0.335
6 Years
7 Years
8 Years
9 Years
10 Years


Varying Time Period of M
M Indicator Values
0.6
0.45
0.3
0.15
0
1998
2001
2004
2007
2010
2013
Tellurium
1 Year
2 Years
3 Years
4 Years
Standard
0.335
6 Years
7 Years
8 Years
9 Years
10 Years


Varying Time Period of I
I Indicator Values
0.8
0.6
0.4
0.2
0
1998
2001
2004
2007
2010
2013
Tellurium
1 Year
2 Years
3 Years
4 Years
Standard
0.335
6 Years
7 Years
8 Years
9 Years
10 Years


Varying Time Period of I
0.8
0.6
0.4
0.2
0
I Indicator Values
1998
2001
2004
2007
2010
2013
Rare Earths
1 Year
2 Years
3 Years
4 Years
Standard
0.335
6 Years
7 Years
8 Years
9 Years
10 Years


Varying Time Period of M
1
0.75
0.5
0.25
0
M Indicator Values
1998
2001
2004
2007
2010
2013
Rare Earths
1 Year
2 Years
3 Years
4 Years
Standard
0.335
6 Years
7 Years
8 Years
9 Years
10 Years