Value Recovery from Used Hard Disk Drives

Presenters
Bill Olson (Seagate)
Carol Handwerker (Purdue)
Wayne Rifer (Green Electronics Council, retired)
Colin Fitzpatrick (University of Limerick)

End-of-Project Webinar
December 14, 2016

A recording of this webinar will be available for six months following the event:
https://inemi.webex.com/inemi/lsc.php?RCID=212edf0415b9816d9665056e6cf
Value Recovery from Used Hard Drives

- Project Team Members
- Statement of Problem
- Circular Economy
- Ostrom Framework
- Used Electronics Value Model and Decision Trees
- Barriers and Opportunities for HDD Value Recovery

- Recommendations and Next Steps

Note: All phones will be on mute during the presentation. Please type question into the chat window.
## iNEMI Value Recovery Project: Participants

<table>
<thead>
<tr>
<th>Name</th>
<th>Company</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carol Handwerker – co-chair</td>
<td>Purdue</td>
</tr>
<tr>
<td>Wayne Rifer – co-chair</td>
<td>GEC (retired)</td>
</tr>
<tr>
<td>Bill Olson – co-chair</td>
<td>Seagate</td>
</tr>
<tr>
<td>Alice Lin; Jeffrey Lee</td>
<td>IST Group</td>
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<tr>
<td>Colin Fitzpatrick</td>
<td>University of Limerick</td>
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<tr>
<td>Gary Spencer</td>
<td>IBM - Geodis</td>
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<tr>
<td>Willie Cade</td>
<td>SUNY-Buffalo</td>
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<td>Tim McIntyre</td>
<td>Oak Ridge National Laboratory</td>
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<td>Alex King</td>
<td>Critical Material Institute</td>
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<td>John Sutherland, Hongyue Jin</td>
<td>Purdue</td>
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<td>Ardesthir Mashhadi, Mostafa Sabbaghi, Sara Behdad, Yosepho, Farzad Mehrpour</td>
<td>SUNY-Buffalo</td>
</tr>
<tr>
<td>Ian Lovell</td>
<td>Teleplan</td>
</tr>
<tr>
<td>Devin Imholte, Ruby Nguyen</td>
<td>Idaho National Laboratory</td>
</tr>
</tbody>
</table>
Phase 1
Results and Action Plan
Phase 1 Metals Recycling: Project Summary

Project Statement

- Metals recovery from electronic product recycling is focused on high-volume, valuable metals that are easily recoverable.
- Current and future electronics will contain small quantities of resources available for recovery but are not currently recovered in today’s recycling infrastructure.
- Trends toward miniaturization, product dematerialization, and the introduction of new heterogeneous materials systems create new challenges with respect to materials supply, materials recovery, and electronics recycling.
- How bad is the current situation and will it get worse?
- What will it take to improve the metals recovery?situation with respect to metals recycling and recovery?

Project Results

- The situation is bad and it’s getting worse
- Recycling and metals recovery are not the answer
Key Findings from Phase 1 - iNEMI Metals Recycling Project

• Answer: “Value Recovery“ in the context of a circular economy

• Key role for iNEMI and its members to play in increasing metals recovery, while promoting sustainable electronics.
  – Focus on value recovery through Design for Sustainability.
  – Focus on innovative designs, business models, technologies, supply chains
  – Focus on community building and self-managing the commons

• Of particular importance is the ability of iNEMI to engage stakeholders to examine new approaches to managing critical resources and increasing value recovery while protecting human health and safety and the environment.

• iNEMI Environmental Leadership: CMI, EG 2015, EGG 2016, ERC 2016,..
Value Recovery: Path Forward

• Develop a voluntary, community-based solution involving adaptive governance systems to self-manage common pool resources (E. Ostrom - 2009 Nobel Prize in Economics)
  – Legislation is not practical or advantageous
  – Path forward is through a multi-stakeholder collaboration that articulates a vision and develops scenarios for enhancing value recovery of electronics and metal resources.

• First challenge was to identify a focus and common goals that can get us started – attract team members and key stakeholders

Value Recovery for Hard Disk Drives
Value Recovery from Used Hard Disk Drives
A Circular Flow of Products Leading to a Circular Economy

- From a linear take-make-waste economy to a circular economy
- Essential to meet expanding global demand for electronics, and the more than “Moore’s Law” for data storage.
- Circular economy will be challenging for electronics due to rapidly evolving product design and material content.
- Large gap between production growth and demand growth
Digital Storage Demand and Disruption

- Solid state drive (SSD) storage increasing in digital storage markets, particularly consumer/mobile
- SSD: $/GB = 4x $/GB HDD and max out at about 256G
- Unit hard disk drive (HDD) sales flat in enterprise due to manufacturing facilities unable to meet demand, but capacity per HDD is increasing
- Cloud storage replacing local storage.

B. Sprecher, R. Kleijn, and G. J. Kramer, 2014

AnandTech, 2016
A Circular Economy

Ellen MacArthur Foundation
PRINCIPLE 1

Preserve and enhance natural capital by controlling finite stocks and balancing renewable resource flows
ReSOLVE levers: regenerate, virtualise, exchange

PRINCIPLE 2

Optimise resource yields by circulating products, components and materials in use at the highest utility at all times in both technical and biological cycles
ReSOLVE levers: regenerate, share, optimise, loop

PRINCIPLE 3

Foster system effectiveness by revealing and designing out negative externalities
All ReSOLVE levers

Ellen MacArthur Foundation
Value recovery in HDD...

• More than SHREDDING and metals recovery - currently dominated by either precious metals or commodity materials (i.e., Al, Fe, glass)

... We can challenge the paradigm...

Value in Reuse

• reuse of used HDDs: OEM-branded & “white label”
• reuse of parts in HDDs: platens, magnets, spindle/bearings
• reuse of REE magnets in other products: motors
• materials recovery: Au, Pd, Al, Fe, REE, He

While addressing data security concerns
Momentum within the community –
Seagate President
‘Hard drives from hard drives”

Seagate and the Critical Materials Institute (CMI) have been examining various approaches to value recovery:

- new technologies for removing and reusing magnets from HDDs
- economic, environmental, and logistics analyses to examine the viability of various scenarios for used HDDs and other used electronics
• Value recovery opportunities in used HDDs that are and are not being captured now.
  – And what is needed to capture them: people and organizations, explicit pathways, new/better technologies and design, business models and relationships...

• Business-model-level initiatives are key to developing a circular economy in HDDs

• Such that businesses across the chain of commerce can function in a coordinated fashion to achieve common value recovery objectives.

• This report begin to define a path to that infrastructure based on diversified and effective value recovery for all stakeholders
Decision to reuse a hard drive should be made based on technological, economic, ecological, social and cultural, and legal aspects.
Reuse of a hard drive in its original form or in a slightly modified form is the best economic and environmental outcome—All environmental impact factors, from carbon footprint to toxicity, are lower for reusing rather than replacing HDDs, even when materials recovery of used HDD is factored in. Reuse/sale of used HDDs is a cheaper alternative to buying a new drive, and does not have a significant impact on the sales of new drives due to increasing global storage demands.
Dramatic Industry Consolidation with Consistent Mechanical Design
How many HDDs are available for value recovery?

Simplified SD model broken down by stocks (boxes) and flows (circles)
Upper and Lower Bounds of HDDs Available for Value Recovery from NA Data centers (adjusting EoL pathways). Grey line indicates average.

**Estimate:** 19-24M HDDs from North American data centers are available for value recovery per year from 2015-2020.
Decision Point:
recertified OEM-branded or “White Label”?  
- Depends on meeting specific SMART or SMART-like criteria set by the specific OEMs for OEM-branded and by “white label” processors based on resulting HDD reliability, price, market demand.  
- “White label” drives may have lower storage capacity than original drives.  
- Specialized software → Authorized OEM service providers
Simplified Recycler Decision Tree

Start

Concerns

1. Security Concerns
   - Security Category of data
   - Device remaining or leaving organization

2. Resale Value of HDD
   - Current HDD resale value. Includes Technology and HDD size, all concerns for resale.
   - Costs to Data Wipe, prepare for sale.
   - Barriers for entry.
   - Potential sale value in “White Label” process.

White Label Process Definition:
1. Alternate Sales Channel. Allows the sale of HDDs not otherwise eligible for resale to a Hard Drive remanufacturer. The Hard Drive Remanufacturer remanufactures the hard drive. Result is a new hard drive ready for sale.
2. White Label sales should be considered as an alternative to shredding or destruction of hard drives.
3. The White Label process allows a full recovery of the component parts of the Hard Drive preserving components for commodity processing.

3. Commodity Pricing
   - Tradeoff of Labor versus Commodity Pricing
   - Overhead costs – space to perform tear down.
   - Market availability.
   - Barriers for entry.

End
What About Data Security?
NIST based Decision tree for disposition of HDDs
Decision Tree for Used HDDs

Start

Receive undamaged HDD

Scan Model for Recovery decision into Floor Control System

Recovery decision?

Scrap

Hard drive contain large circuit card?

Yes

Remove Circuit card and sell as Precious Metal

Hard Drive Carcass

Circuit Card Precious Metal

No

Shred Hard Drive to destroy data

Mixed Aluminum

Sell at Commodity level

End
Punched or bent HDDs, performed at HDD owner’s facility, sometimes followed by shredding – removes reuse option.
Value Recovery Workflow

Aggregation Pathways
Fig. 8. Transformation of pre-processing methods for desktop computer influenced by increasing labor costs in China (2000–2009, statistic data; 2010–2035, forecast). When labor cost increases, mechanical separation gradually replaces manual dismantling, in order to gain profit (shift from zone A–B and finally C to be economically advantageous).
Creating New Rare Earth Sources - Dismantling

- Ultra-high speed (>350mm/sec) robotic end mill technology used to remove fasteners
- Multi-output streams recovered undamaged
- Multi-reuse applications are enabled

• ~1 HDD processed every 4 seconds
• HDDs are singulated, aligned then dismantled
• HDD components recovered undamaged - Reuse

First HDD direct reuse experiment by Seagate – Can we reuse the magnet assembly?
New Pathways for Value Recovery

Start

Receive undamaged HDD

Scan Model for Recovery decision into Floor Control System

Recovery decision?

Scrap

Reuse

Run SMART test to verify functionality of Hard Drive

Pass SMART Test?

Yes

No

Perform Data Wipe

Pass Data Wipe?

Yes

End

No

New Pathways for Value Recovery

Hard drive contain large circuit card?

Yes

No

Remove Circuit card and sell as Precious Metal

Hard Drive Carcass

Sell at Commodity level

Circuit Card Precious Metal

Mixed Aluminum

Shred Hard Drive to destroy data

Considerations when deciding the level to disassemble a HDD:
2. Technology — difficulty to separate components. Size of Screws, Number of Screws.
3. Commodity prices — Precious metals, etc.
4. Amount of recovery material — size of drive.
5. Manufacturer HDD — different assembly techniques.
HDD Disassembly for Part Reuse

1. Evaluate Hard Drive for Re-use or recovery
   - If yes, go to step 2; if no, go to Shred.

2. Separate PCB?
   - Yes: Remove PCB, go to PCB Sent to Smelter - $8/lb; No: go to Carcass.

3. Carcass
   - Shred sent for Aluminum Mix

4. Shred
   - No - Hard Drive parts for recycling

5. Re-use PCB?
   - Yes: Remove PCB, go to PCB Retained for re-use; No: go to Carcass.

6. Re-use Platen?
   - Yes: Remove Platen, go to Platen for reuse; No: go to Shred.

7. Re-use Spindle Bearings?
   - Yes: Remove Spindle Bearings, go to Spindle Bearings for reuse; No: go to Shred.

8. Re-use Spindle Motor?
   - Yes: Remove Spindle Motor, go to Spindle Motor for reuse; No: go to Shred.

9. Re-use Read Head?
   - Yes: Remove Read Head, go to Read Head for reuse; No: go to Shred.

10. Reuse Casing?
    - Yes: Remove Casing, go to Casing for reuse; No: go to Shred.

11. Reuse Magnets?
    - Yes: Remove Casing, go to Magnets for reuse; No: go to Shred.
HDD Part Reuse for Alternative Applications

- PM Alloy
- Separated REE
- Swarf Processing (3.1.5.2)
- Swarf
- Direct Reuse
- DfX (3.1.5.4)
- Design & Production
- Altered (New) Reuse
- Distribution/Consumption
- End of Life Product Recovery (3.1.5.1, 3.1.5.3)
- Landfill
- Optimal Dismantling for Value Recovery (3.1.5.4)
- TEA (3.1.5.5)
Conducted a survey to
- explore the barriers to implementing these solutions
- identify how these barriers might be overcome

<table>
<thead>
<tr>
<th>Actor</th>
<th>Number of Participants</th>
</tr>
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<tbody>
<tr>
<td>HDD Manufacturer</td>
<td>2</td>
</tr>
<tr>
<td>HDD User</td>
<td>3</td>
</tr>
<tr>
<td>Used HDD Processor</td>
<td>9</td>
</tr>
<tr>
<td>Recycler</td>
<td>7</td>
</tr>
<tr>
<td>University/Research Institute/Other</td>
<td>11</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>23</strong></td>
</tr>
</tbody>
</table>
Implementing the Circular Economy for HDD

Barriers to **direct reuse**
- Data security: risk versus benefits
- Economic viability

Overcoming these barriers requires
- Providing to HDD owners/users
  - Education HDD users/owners on the reliability of data wiping
  - Greater assurances, including quantitative data, on the reliability and quality of data removal from HDDs
- Developing
  - More effective processes to keep more HDDs in reuse stream, including new business relationships
  - Better quantification of the relationship between reliability indicators (e.g. SMART) and remaining HDD lifetime

Involves:
- HDD Manufacturers
- HDD users
- Data wiping software providers
- IT Asset Managers
- OEM-authorized service providers
- Equipment manufacturers
Barriers to **dismantling**

- Cost

Overcoming these barriers requires

- Design HDD to be dismantled
- Automation: speed and quality

Involves

- HDD Manufacturers
- Recyclers, dismantlers
- Research institutes
Implementing the Circular Economy for HDD

Barriers to **parts reuse**
- Cost (must be dismantled to being with)

Overcoming these barriers requires
- Design HDD to be dismantled and parts to be reused
- Standardisation of parts across ranges and manufacturers
- Guidelines on reusability from a quality and compatibility perspective

Involves
- HDD manufacturers
- HDD users/owners
- OEM authorized service providers
Barriers to *parts sorting*

- Cost (time taken)

Overcoming these barriers requires

- Automation

Involves

- HDD Manufacturers
- Pre-processors
- End-processors
Each of these barriers does not seem insurmountable

BUT
To overcome them is beyond the capacity of any individual actor

SO
It will require significant co-operation and collaboration across the life cycle with individual agents taking a broader perspective than currently prevails

THUS
Ostrom framework offers a mechanism to do so
Question is whether there is the will
**Social, economic, and political settings (S)**
- S1 Economic development.
- S2 Demographic trends.
- S3 Political stability.
- S4 Government resource policies.
- S5 Market incentives.
- S6 Media organization.

<table>
<thead>
<tr>
<th>Resource systems (RS)</th>
<th>Governance systems (GS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RS1 Sector (e.g., water, forests, pasture, fish)</td>
<td>GS1 Government organizations</td>
</tr>
<tr>
<td>RS2 Clarity of system boundaries</td>
<td>GS2 Nongovernment organizations</td>
</tr>
<tr>
<td>RS3 Size of resource system*</td>
<td>GS3 Network structure</td>
</tr>
<tr>
<td>RS4 Human-constructed facilities</td>
<td>GS4 Property-rights systems</td>
</tr>
<tr>
<td>RS5 Productivity of system*</td>
<td>GS5 Operational rules</td>
</tr>
<tr>
<td>RS6 Equilibrium properties</td>
<td>GS6 Collective-choice rules*</td>
</tr>
<tr>
<td>RS7 Predictability of system dynamics*</td>
<td>GS7 Constitutional rules</td>
</tr>
<tr>
<td>RS8 Storage characteristics</td>
<td>GS8 Monitoring and sanctioning processes</td>
</tr>
<tr>
<td>RS9 Location</td>
<td></td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Resource units (RU)</th>
<th>Users (U)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RU1 Resource unit mobility*</td>
<td>U1 Number of users*</td>
</tr>
<tr>
<td>RU2 Growth or replacement rate</td>
<td>U2 Socioeconomic attributes of users</td>
</tr>
<tr>
<td>RU3 Interaction among resource units</td>
<td>U3 History of use</td>
</tr>
<tr>
<td>RU4 Economic value</td>
<td>U4 Location</td>
</tr>
<tr>
<td>RU5 Number of units</td>
<td>U5 Leadership/entrepreneurship*</td>
</tr>
<tr>
<td>RU6 Distinctive markings</td>
<td>U6 Norms/social capital*</td>
</tr>
<tr>
<td>RU7 Spatial and temporal distribution</td>
<td>U7 Knowledge of SES/mental models*</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Interactions (I) → outcomes (O)</th>
<th>Related ecosystems (ECO)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I1 Harvesting levels of diverse users</td>
<td>ECO1 Climate patterns. ECO2 Pollution patterns. ECO3 Flows into and out of focal SES.</td>
</tr>
<tr>
<td>I2 Information sharing among users</td>
<td></td>
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<tr>
<td>I3 Deliberation processes</td>
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<tr>
<td>I4 Conflicts among users</td>
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<td>I5 Investment activities</td>
<td></td>
</tr>
<tr>
<td>I6 Lobbying activities</td>
<td></td>
</tr>
<tr>
<td>I7 Self-organizing activities</td>
<td></td>
</tr>
<tr>
<td>I8 Networking activities</td>
<td></td>
</tr>
</tbody>
</table>

*Subset of variables found to be associated with self-organization.
Key Conditions Necessary for Self-Management of Common Pool Resources

1. System dynamics need to be sufficiently predictable
2. Number of users are well known and are of limited numbers, so that the stakeholders can be identified and included in organization.
3. Leadership exists – The electronics industry is well organized by industry associations and certain large companies are recognized as leaders. In terms of sustainability, iNEMI, the US EPA, and others have brought together key stakeholders to develop future scenarios and roadmaps to sustainability.
4. Users of…resource systems…share moral and ethical standards regarding how to behave in groups – The industry has worked well together on many initiatives, e.g. RoHS transition, iNEMI, EICC, IEC & EPEAT standard development.
5. Recognized importance of resource to users – The increasing reliance of electronic products on the performance of certain technology metals, and the presence of geopolitical risks to their supply, have been well documented. In addition, EoL electronics have been recognized as objects of potential value, whether for reuse, remanufacturing, or recycling.
Recommendations
In order to unlock value recovery we must intentionally design for that outcome.

The intent is to extend the working life of HDD’s by all possible means.

Open up New markets and channels for used electronics.

OEM’s must design the HDD for maximum value recovery.
New Pathways for Value Recovery

Used HDD’s are just one type of consumer electronic product. This approach can be applied to all forms.

The proposed path requires a fundamentally new approach to consumer electronics design and life cycle management.

Implement the Ostrom framework to maximize the value of used equipment through Circular Economy based life cycle management.

Considerations when deciding the level to disassemble a HDD:
1. Cost of Labor/Overhead
2. Technology – difficult to separate components: size of screws, number of screws
3. Commodity prices – precious metals, etc.
4. Amount of recovery materials – size of drive
5. Manufacturer HDD – different assembly techniques.
Thanks!
Supporting Content
Key Resources for iNEMI Value Recovery Project

• Phase I iNEMI Report on the State of Metals Recycling
  – [link]

• Dr. Eleanor Ostrom framework for developing voluntary, community-based solutions, involving adaptive, self-governing systems that effectively manage common pool resources
  – [link]

• The challenge for a circular economy from the Ellen Macarthur Foundation
  – www.ellenmacarthurfoundation.org/circular-economy/overview

• The European Commission Action Plan for a Circular Economy
Table 2 – Rare earth magnet applications and oxide requirements

<table>
<thead>
<tr>
<th>Applications</th>
<th>yr 2010</th>
<th>2010</th>
<th>yr 2015</th>
<th>2015 PROJECTED</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>% of mix</td>
<td>Magnet</td>
<td>Oxide, tons</td>
<td>Magnet</td>
</tr>
<tr>
<td>Motors, industrial, general auto, etc</td>
<td>25.5%</td>
<td>15,871</td>
<td>7,122</td>
<td>1,059</td>
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<tr>
<td>HDD, CD, DVD</td>
<td>13.1%</td>
<td>8,140</td>
<td>4,196</td>
<td>0</td>
</tr>
<tr>
<td>Electric Bicycles</td>
<td>9.1%</td>
<td>5,680</td>
<td>2,549</td>
<td>379</td>
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<tr>
<td>Transducers, Loudspeakers</td>
<td>8.5%</td>
<td>5,290</td>
<td>2,727</td>
<td>0</td>
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<tr>
<td>Unidentified and All Other</td>
<td>6.5%</td>
<td>4,046</td>
<td>1,995</td>
<td>90</td>
</tr>
<tr>
<td>Magnetic Separation</td>
<td>5.0%</td>
<td>3,112</td>
<td>1,466</td>
<td>138</td>
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<tr>
<td>MRI</td>
<td>4.0%</td>
<td>2,490</td>
<td>1,228</td>
<td>55</td>
</tr>
<tr>
<td>Torque-coupled drives</td>
<td>4.0%</td>
<td>2,490</td>
<td>1,117</td>
<td>166</td>
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<tr>
<td>Sensors</td>
<td>3.2%</td>
<td>1,992</td>
<td>982</td>
<td>44</td>
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<tr>
<td>Hysteresis Clutch</td>
<td>3.0%</td>
<td>1,867</td>
<td>879</td>
<td>83</td>
</tr>
<tr>
<td>Generators</td>
<td>3.0%</td>
<td>1,867</td>
<td>769</td>
<td>194</td>
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<tr>
<td>Energy Storage Systems</td>
<td>2.4%</td>
<td>1,494</td>
<td>670</td>
<td>100</td>
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<tr>
<td>Wind Power Generators</td>
<td>2.1%</td>
<td>1,300</td>
<td>583</td>
<td>87</td>
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<tr>
<td>Air conditioning compressors and fans</td>
<td>2.0%</td>
<td>1,245</td>
<td>559</td>
<td>83</td>
</tr>
<tr>
<td>Hybrid &amp; Electric Traction Drive</td>
<td>0.9%</td>
<td>570</td>
<td>214</td>
<td>80</td>
</tr>
<tr>
<td>Misc: gauges, brakes, relays &amp; switches, pipe inspection, levitated transportation, reprographics, refrigeration, etc.</td>
<td>7.7%</td>
<td>4,792</td>
<td>2,186</td>
<td>285</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>100.0%</strong></td>
<td><strong>62,246</strong></td>
<td><strong>29,243</strong></td>
<td><strong>2,843</strong></td>
</tr>
</tbody>
</table>

REO requirement includes 80% oxide to metal, 97% metal alloying, and 80% magnet manufacturing material yields.

Constantinides, 2011
Current HDD Value Recovery Pathways

Start

Security Concerns
1. Security Category of data
2. Device remaining or leaving organization

Resale Value of HDD
2. Costs to Data Wipe, prepare for sale.
3. Barriers for entry.
4. Potential sale value in “White Label” process.

Commodity Pricing
1. Tradeoff of Labor versus Commodity Pricing
2. Overhead costs – space to perform tear down.
4. Barriers for entry.

End

White Label Process Definition:
1. Alternate Sales Channel. Allows the sale of HDDs not otherwise eligible for resale to a Hard Drive remanufacturer. The Hard Drive Remanufacturer disassembles the hard drive and then reassembles the hard drive with new components. Result is a new hard drive ready for sale.
2. White Label sales should be considered as an alternative to shredding or destruction of hard drives.
3. The White Label process allows a full recovery of the component parts of the Hard Drive preserving components for commodity processing.
HDD Categories/Markets

1. Mobile Consumer
2. Desktop
   - Consumer Desktop
   - Business-Critical (BC) Enterprise (i.e., Nearline, Reference)
3. Mission-Critical Enterprise

- DC HDDs have high value recovery potential
  - Concentrated in larger volumes
  - Relatively higher capacity and value per drive

*There are DCs today that use Consumer Desktop HDDs in place of the Enterprise-class models (BackBlaze, 2016). However, it is unclear to what extent this is industry practice.
How can we estimate DC HDD availability for value recovery?

- Stocks and Flows Analysis using System Dynamics
- Account for North America (NA) HDD sales, HDD models, failure rates and warranty replacements
Depending on the extent that HDDs are shredded or otherwise not recovered, ~19-24M HDDs could be expected to be available for value recovery from NA DCs from 2015-2020.
Motors from HDD Magnet Assemblies

Three Phase Voltage and Current Waveforms at ~150 rpm

- Shown to the left are the 3-phase voltages at the top of each figure and the 3-phase currents on the bottom for two different operating speeds (150 & 300 RPM).
- Rotational speeds, torque curve, back EMF and other parameters will be used to optimize motor performance.

Three phase voltage (line to neutral), and three phase current.

Three Phase Voltage and Current Waveforms at ~300 rpm

Three phase voltage (line to neutral) 5V/div, and three phase current 2A/div.
Creating New Rare Earth Sources

Punching

- Punching provides extremely rapid (1 HDD/sec) separation of the magnet assembly region of the HDD
- Custom punch design can be very effective for large quantities of similar HDDs

Observations
- Steel lid follows punch shape
- Aluminum case fractures at magnet assembly
- Magnet assembly intact
- Magnets damaged may be by VC arm during punching
Creating New Rare Earth Sources from Shredded Hard Drives

- Perceived as most data secure method of HDD recycling
- Also perceived as diminishing ability to recover maximum value → send shredded material to metal recycler
- Most widely adopted HDD recycling method

Discussions ongoing with HDD shredder companies

The output from “general purpose” shredder unpredictable

NdFeB recovered from shreds

~80%

100.7% mass of Input
Environmental Impact Assessment

## Final product: NdFeB Magnet

<table>
<thead>
<tr>
<th>Impact category</th>
<th>Unit</th>
<th>Virgin (A)</th>
<th>Recycled (B)</th>
<th>(B)/(A) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global Warming</td>
<td>kg CO₂ eq</td>
<td>27.602</td>
<td>12.453</td>
<td>45.12%</td>
</tr>
<tr>
<td>Acidification</td>
<td>H⁺ moles eq</td>
<td>20.524</td>
<td>11.320</td>
<td>55.15%</td>
</tr>
<tr>
<td>Carcinogenics</td>
<td>benzene eq</td>
<td>0.069</td>
<td>0.035</td>
<td>49.66%</td>
</tr>
<tr>
<td>Non carcinogenics</td>
<td>toluene eq</td>
<td>249.382</td>
<td>136.075</td>
<td>54.56%</td>
</tr>
<tr>
<td>Respiratory effects</td>
<td>kg PM2.5 eq</td>
<td>0.124</td>
<td>0.059</td>
<td>47.51%</td>
</tr>
<tr>
<td>Eutrophication</td>
<td>kg N eq</td>
<td>0.011</td>
<td>0.004</td>
<td>33.61%</td>
</tr>
<tr>
<td>Ozone depletion</td>
<td>kg CFC-11 eq</td>
<td>1.25E-06</td>
<td>4.89E-07</td>
<td>39.28%</td>
</tr>
<tr>
<td>Ecotoxicity</td>
<td>kg 2,4-D eq</td>
<td>94.285</td>
<td>45.345</td>
<td>48.09%</td>
</tr>
<tr>
<td>Smog</td>
<td>kg NOX eq</td>
<td>0.109</td>
<td>0.034</td>
<td>30.98%</td>
</tr>
</tbody>
</table>

Value Path Decision Making: Operations Perspective

Considerations when deciding the level to disassemble a HDD:
2. Technology – difficulty to separate components. Size of Screws, Number of Screws.
3. Commodity prices – Precious metals, etc.
4. Amount of recovery material – size of drive.
5. Manufacturer HDD – different assembly techniques.
Guide for Economic Decision Making