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Life-Cycle of Large Radiological Sources-Assessing RDD Concerns & Options

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Abstract- *The possible use of large radiological sources in Radiation Dispersal Devices (RDDs), a.k.a., dirty bombs, is a major concern because of their widespread usage and vulnerability to theft. Vulnerabilities in the life-cycles of the large radiological sources were assesses using a Source Status Concern Index (SSCI), which takes into account the number of sources, their radioactivity levels and hazards posed, and the source accessibility and security. Identified priorities included cobalt source transportation and teletherapy users. A range of options for reducing the vulnerabilities of the most problematic sources was evaluated using the SSCI approach, and an integrated approach of improved international agreements/ regulations, aggressive disused/orphan source recovery and physical security, and alternate technologies could reduce the overall vulnerability by around 90% within a decade.*

I. INTRODUCTION

Radioactive materials provide benefits to mankind in many fields, with dozens of radiological source producers and suppliers spread across six continents, and on the order of a billion sources in use world-wide.[1, 2] The growth in terrorism has increased concerns about whether some of the same radiological sources could be used in radiation dispersal devices (RDDs). Although there are many variables that can make an RDD attack much worse, a key factor is the quantity and type of radiological source material that is dispersed. Because there are far more relatively inconsequential radiological sources in use than there are large sources, this provides an important focusing element in reducing the RDD threat, namely to reduce access to large and potentially hazardous RDD source materials. Completion of an initial global assessment of the large radiological sources available at different stages of their life-cycles supported development of a Source Status Concern Index (SSCI). The SSCI is a measure of the vulnerabilities associated with each of the large source applications at each of the stages in their life cycle. Assessment of the current situation regarding large radiological sources indicates many areas of high concern, especially related to user facilities, transported, and disused and orphan sources. There are various options available to reduce the vulnerabilities , including recovery of disused and orphan sources, security upgrades for vulnerable facilities, improved international agreements and regulatory structures, and the substitution of alternate technolo-gies. Such options were assessed using the SSCI analysis. Significant risk reduction appears to be possible, but progress must come on several fronts in order to obtain a significant reduction in risk.

II. CANDIDATE RADIOACTIVE MATERIALS

At the most fundamental level, radiological sources are used for three purposes: (1) to kill or otherwise alter organisms or tissue, (2) to generate energy on a localized and/or remote basis, or (3) to scan objects or provide other types of measurements. A hierarchy of radiological sources, grouped in terms of these three purposes, is provided in Figure 1. The sources near the top of the chart can utilize thousands, and sometimes millions, of curies of radioactive materials, whereas something nearer the bottom of the chart uses a very small fraction of that amount of radioactivity.

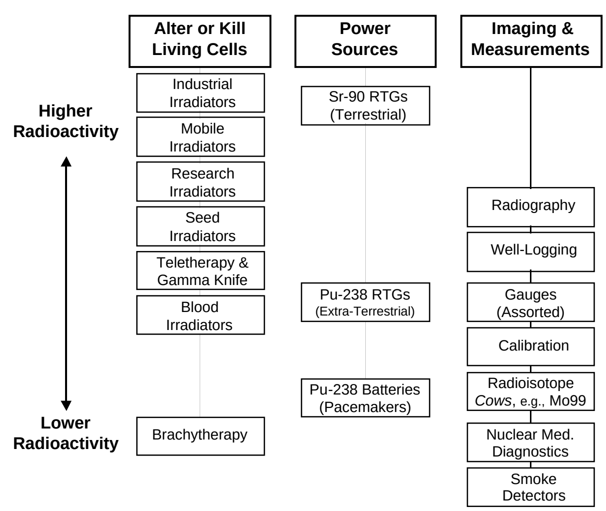

Fig. 1 Hierarchies of Radiological Source Applications

Applications involving the largest radioactive sources are included in Figure 2, which also includes the typical radioisotopes and activity levels.[3] Only a few radioisotopes are utilized in the larger applications. The largest industrial sterilization units use cobalt-60 sources in facilities that number around 190 world-wide.[2] Smaller units that are sometimes mobile use cesium-137, as it is easier to shield. There are more than 100 research irradiators, and many of them use cesium-137. The former Soviet unit deployed many mobile seed irradiators, which are now obsolete. Teletherapy units are used to irradiate cancer tumors, and usually use cobalt-60 to produce the gamma radiation. There are about 5300 of these, mostly outside the U.S.[5] Most blood irradiators are located in Western countries, and use cesium-137 to kill antibodies in blood prior to transfusions. These are thought to number between 1000 and 2000 worldwide. Radioisotopic Thermal Generators (RTGs) are based primarily on large amounts of the beta-emitting strontium-90 (about 1000 such units), although there have been a few plutonium-238 RTGs (mostly for space exploration).[6] Radiography units are commonly used to scan industrial welds, mostly using iridium-192. Well-logging sources are similar except they used neutron sources to probe the geology around oil-well shafts.[7]

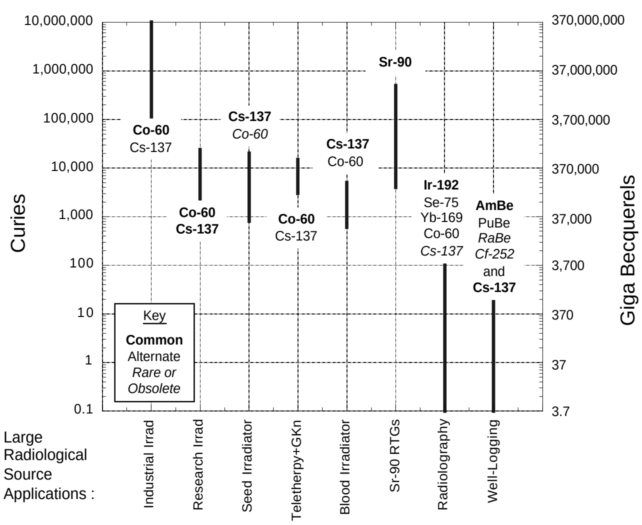

Fig. 2 Radioactivity Ranges of Large Radiological Source Applications

An important limitation in Figure 2 is that the comparison is made in terms of radioactivity levels, whereas the potential RDD impact would be more closely related to radiation dose. If a one-curie radiation source is one meter from a person, the direct radiation dose to that human is estimated in rems per hour at one meter. If someone ingests or inhales one curie of a radioactive material, the cumulative dose to that person over the next fifty years can also be estimated. These numbers form the basis for Table 1, which also includes normalization against the potential dose impacts from the dose from cobalt-60.[8]

Table1. Radiation dose relative to Co-60 for radioisotopes used in large sources.[8]

Isotope	Half-life	RHM Note 1	CDE Ingest Note 2	CDE Inhale Note 2	RHM/ RHM,Co	Ingest/ Ingest,Co	Inhale/ Inhale,Co
Co-60	5.3 yr	1.37	26900	219000	1.0	1.0	1.0
Cs-137	30.1 yr	0.38	50000	31900	0.3	1.9	0.1
Ir-192	74 d	0.59	5740	28100	0.5	0.2	0.1
Sr-90	29.1 yr	0.00	142000	1300000	0.0	5.3	5.9
Pu-238	88 yr	0.08	3200000	392000000	0.1	119.0	1790.0
Ra-226	1600 yr	0.01	1320000	8580000	0.0	49.1	39.2
Am-241	433 yr	0.31	3640800	444000000	0.2	135.3	2027.4
Cf-252	2.6 yr	0.04	1084100	136900000	0.0	40.3	625.1

Note 1: Rem per hour at 1 meter per curie Note 2: 50 year cumulative dose, per curie

Source: Handbook of Health Physics & Radiological Health by Shleien

There are others factors that can raise or lower the RDD risk. Some are related to ease or difficulty in acquiring, transporting, dispersing the source. Radioactive materials with short half-lives could present difficult constraints. Heat is a problem for larger sources, and infrared detectors commonly used at border crossings will *light-up* in response to temperatures less than one degree above ambient temperatures. There is also a concern about the potential contamination, and some sources are more problematic than others.

Companies in six different countries currently supply large amounts of cobalt-60, cesium-137, and/or strontium-90, and usually provided the applications, as well. Fig. 3 identifies the largest isotope producers in the world. **MDS Nordion**, a Canadian company, produces roughly 80% of the world's supply of cobalt, and is the largest supplier of reactor-produced isotopes for teletherapy, blood irradiation, and industrial irradiation, and also manufactures and installs irradiation facilities around the world.[9] **REVISS** (Russian/English Venture in Isotope Supply Services) produces cobalt-60, cesium-137, and strontium-90, and has also been a large producer of RTGs. **CNEA** Argentina (National Commission of Atomic Energy) has emerged as a large producer of cobalt-60, and claims to control approximately 10% of the cobalt market, with the US and Canada being the largest recipients of Argentinean cobalt. Nuclear Technology Products (**NTP**) is the commercial division of the South African Nuclear Energy Corporation (NECSA). NTP produces cobalt-60 and cesium-137. India's Board of Radiation and Isotope Technology (**BRIT**) supplies all of India with cobalt and cesium. Its annual production of cobalt-60 is roughly 2-3 million curies. BRIT also turns out teletherapy machines, and began designing blood irradiators (using cobalt-60) in

2000, both for distribution largely within India. The Institute of Isotopes (**IZOTOP**) in Hungary has been producing isotopes since 1964, focusing on manufacturing cobalt sources for teletherapy and industrial irradiation.

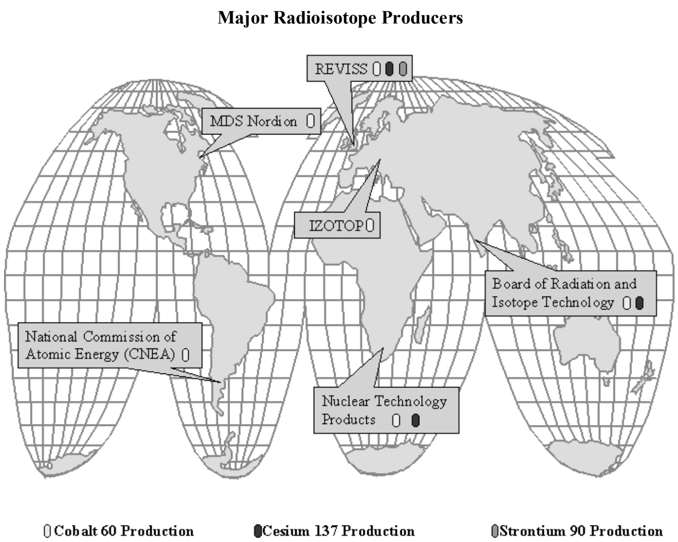

Fig. 3 Large-Scale Manufacturers of Radioisotopes

A second-tier of isotope producers generates much smaller quantities of radioactive sources in comparison to the previous group. Often these companies supply only their country or geographic region with smaller curie amounts, e.g. teletherapy sources as opposed to industrial irradiation sources. Additionally, these businesses and research institutes will often receive radioactive material from the first tier of producers. A third-tier of producers exists, and includes organizations that have either significant isotope-production capabilities or are known to produce isotopes in unknown quantities. Most of these potential producers have nuclear reactors, however the information regarding their usage is extremely limited.

The largest users of radiological sources are western countries and parts of the former Soviet Union, although one would be hard pressed to find countries where radiological sources are not in use. The large irradiators and the RTGs also tend to be mostly Western (especially the U.S) and Soviet devices. The large medical applications, especially the teletherapy units, can be found almost anywhere. Their spread was aided by the IAEA and U.S. organizations finding new homes for units replaced by accelerators during the 1970s and 1980s. Blood irradiators have not yet propagated as widely. Radiography sources are widely available, and they are commonly available at construction sites in many parts of the world. Well-logging sources are also widely used, although by a handful of multi-national corporations.

There is no standard procedure for regulating radioactive sources internationally. Each system of practice varies remarkably from country to country. In 2000, the IAEA issued its "Code of Conduct on the Safety and Security of Radioactive Sources" in an attempt to cultivate "a high level of safety and security of radioactive sources through the development, harmonization, and enforcement of national policies, laws, and regulations, and through the fostering of international cooperation.".[10] The IAEA realized that this Code of Conduct is inadequate in a "post 9-11" environment, and is currently in the process of revising its recommendations. The new code will continue to focus on regulatory infrastructure, source management and control, source categorization, orphan source response, information exchange, education and training, and international support. The laws regulating the import, export, and return of sources, the definitions of ownership and operational lifetime of sources, the proper design and manufacture of sources, and the registries of sources are all still being debated.[11]

Owners of used radiological sources have limited options for source disposal, and some of the options can be very expensive. Recycle is the most attractive option, and in the case of a valuable material such as cobalt, the owner can get money back. But most used source materials have little value, so the owner must pay to dispose of the used source. Waste consolidation or disposal sites are available in some countries, but the options are very limited in others. Source disposal often defaults to one of three undesirable cases: re-sale to another user- often in another country, storage in a disused state, or orphaned/abandoned.

III. LIFE-CYCLE OF RADIOLOGICAL SOURCES

The life-cycle of radiological source materials / sources is illustrated in Fig. 4. Isotope production is usually in nuclear reactors, although some smaller radiological source materials are produced using particle accelerators. Some post-processing is involved in isolating the radionuclides of interest, and this is usually associated with the isotope production facility (reactor). Source fabrication is usually a mechanical/metallurgical processing step that could be co-located with the radionuclide producers, but could be a separate business. To the extent recycling of materials such as cobalt-60 is performed, it is most likely co-located with the producer. Radiological source users are nearly always located separately from the producers, sometimes introducing some lengthy transportation routes. Ideally, when the user has finished using the source, he will return the source for recycling or will ship it to a disposal site. Difficulties in doing so, however, lead to either a disused source being retained indefinitely at the user facility, or even worse, the loss of the source rendering it into the orphan category.

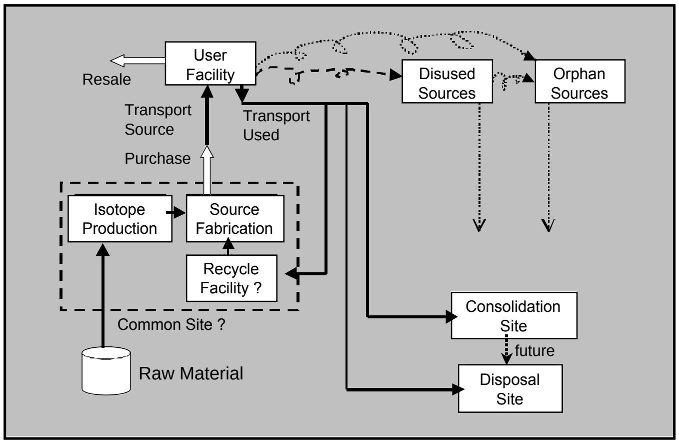

Figure 4. Life-Cycle of Radiological Source Materials

In terms of the vulnerability of sources to theft by terrorists intent on dispersing radiation in an act of terror, different points in the life-cycle present different concerns. The largest concentrations of materials are generally at production sites, but that is where the security will be greatest. User facilities can contain large amounts of dangerous radiological sources, and the security may be minimal depending on the purpose of the facility. The orphans present some well-publicized concerns, as they are very vulnerable if someone stumbles upon them. Disposal sites are uncommon in many parts of the world, and most of the sites that are open are used mostly for low-level wastes of little concern. The transportation piece could be very vulnerable, although it would be difficult to hi-jack a truck without drawing considerable attention from law-enforcement personnel.

IV. SOURCE STATUS CONCERN INDEX (SSCI)

There is vulnerability associated with each type of large radiological source applications at each stage in the life-cycle. The concern can vary by many orders of magnitude, and depends on several factors. In this section we'll focus on the factors that contribute to concern and how these vary. Five factors have been identified, namely the number of sources, the radioactivity levels of the sources, the hazard factor for a given material type, the inaccessibility of the sources, and a source security factor. There are doubtless many ways to define a Source Status Concern Index (SSCI) based on these five parameters. Two desirable characteristics of such an index are simplicity and that it reflects the order of magnitude nature of the problem. The best-known example of an order of magnitude scale is the Richter scale, which is a measure of the severity of earthquakes. An equivalent measure can be derived from the five parameters:

SSCI : Log_{10}(#Sources x Radioactivity Level x Hazard Factor/Inaccessibility/Security) (1),

Where:
Sources = number of sources of a given application type at a specific stage of the life-cycle
Radioactivity Level = Typical/average radioactivity level in curies of source type at life-cycle stage
Hazard factor = On a scale of 1 to 100, how great is the concern on a per curie basis (consistent with the priority bar defined in Section 4.2 (100 is high, e.g. plutonium)
Inaccessibility = score on scale of 1 to 100, with 100 being the more inaccessible sources
Security = score on scale of 1 to 100, with 100 reflecting highest security features

V. SSCI ANALYSIS –CURRENT CONCERNS

As described earlier, the number of large radiological sources in use is relatively well known, with the exception of the radiography sources. For the radiography sources, roughly 12, 000 new sources are supplied every year. Since most radiography sources are short lived, we can infer that the total number in use is probably in the range of 20, 000 to 30, 000. Based on these known or semi-known quantities and some reasonable assumptions, we developed the top part of Table 2. Because the industrial irradiators use cobalt-60, which is commonly recycled, one can infer a re-supply chain that provides new source materials at least every couple of years (taking back used sources), and small quantities of disused, orphaned, or disposed of sources. The research irradiators use either cesium or cobalt sources, so the assumed numbers are more of a composite, with some problematic used sources. Seed irradiators are unique, in that they are nearly all believed orphaned. Most teletherapy sources and gamma-knifes use cobalt, so again the problematic used sources are not thought to be common. However, there remain a few cesium units, so there might be a few disused cesium sources in the mix. Blood irradiators are newer, so the projected problem cases are few at this time. The RTGs are nearly as unique as the seed irradiators, as many of the units are either very old or abandoned in place. One mystery is the extent to which the Russians might replace the old units, should they be recovered and dismantled. The assumptions about disused, orphaned, consolidated, and disposed radiography sources are based on extrapolations from the supply stream. However, most radiography sources decay quickly (months), so this radioactivity levels for these sources fall quickly, making the actual number of used radiography sources a less significant parameter. Regarding the well-logging sources, a few oil exploration companies are known to possess the bulk of the disused sources.

The nominal radioactivity levels of large radiological sources are fairly well known, although the radioactivity level changes with time. The values in Table 2 and utilized in the study reflect the nominal sizes of the most typical large radiological source applications. The impact of the radioactivity decay is approximated through the life-cycle, and most apparent with the short-lived radiography sources. We have assumed that sources do not move quickly into disused condition, and that significant delays occur before disposal. We have also assumed that suppliers will typically possess up to a year's supply of sources, although perhaps less with the short-lived radiography sources.

In defining the hazard factors, we've limited ourselves to a simple dose-based model. There are two reasons for this practice. First, some applications use a few different isotopes and chemical forms, so a form of averaging would be needed anyway. But more importantly, our assessment of the most hazardous RDD materials is best held closely. The beta-emitting strontium-90 receives the lowest hazard score. The gamma-emitters are lumped together at 10, and the alpha emitters used in well-logging source are scored at 100.

Inaccessibility is a measure of how difficult it is to be in the proximity of a radiological source. The scores range from 1 to 100 (least accessible), as shown in Table 2. Sources in the possession of suppliers or buried within a disposal site are assumed to be least accessible (100). Radiolography sources and orphaned seed irradiators are notoriously accessible, and are scored at 1. Accessibility through sales (fraudulent) varies, in that certain types of sources are nearly impossible to buy (RTGs, Seed Irradiators, and industrial irradiators) unless the supplier and buyer are very well known to each other. Transportation places all sources in accessible positions (except for seed irradiators, which aren't really sold or shipped). Most sources in use are somewhat accessible, although one doesn't easily walk into an industrial irradiator or access its dangerous source. Disused and orphan sources are more vulnerable than sources in use, but their likely locations vary, as does their accessibility. It is assumed that all waste consolidation sites have some access limitations, such as those at nuclear research facilities.

Some radiological source applications are provided physical security features, involving technology and/or security personnel. It is important to factor security into our analysis, but it is equally important that we not reveal some of the more subtle differences in the security of different types of radiological sources. Therefore, the values included in Table 2 are once again approximations to the actual situation. As can be seen, we have differentiated primarily between stages in the life-cycle. Suppliers and disposal sites will generally have some significant security, although some improvement may be possible. Orphans will almost never have any security, unless they happen to be lost inside a secure facility (possible, but not likely to be common). We've assumed some mid-range security features for most categories, including most applications. Regarding users, the security at industrial irradiators is quite apparent and hardly surprising, and the security of radiography sources is notoriously lacking, so we have scored those appropriately.

Based on Eq. 1 and values specified in Table 2, we generated SSCI scores for each of the eight large radiological source applications in each of the life-cycle stages. The results are displayed graphically in Fig. 5. The life-cycle stages are displayed from left to right. The eight trace lines correspond to the large source applications, as indicated in the key on the right side. If one interprets Fig. 5 with a little care, a very important and credible picture

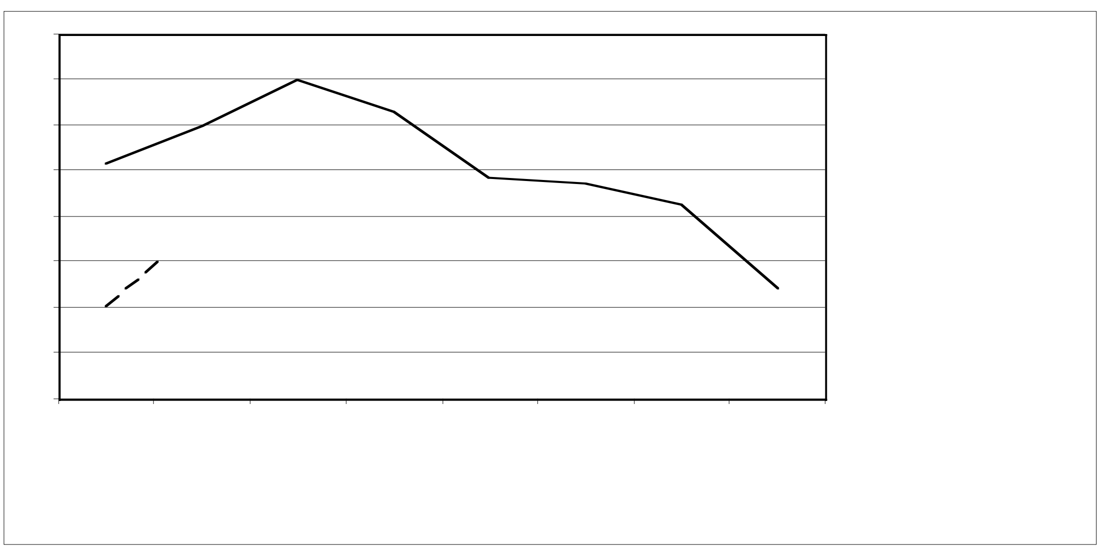

Figure 5. SSCI Results for Large Radiological Sources Throughout Life-Cycle

emerges. Out of the 64 scores, 8 are between 6 and 7, and represent the greatest concern. Another 12 scores fall between 5 and 6 and are very significant concerns. Because of the Log_{10} scale, scores below 5 indicate source status significantly below the top 8 and probably below the next group of 12.

Starting from the left side of the graph, with the production and supplier stage, the Cobalt-60 suppliers are the only suppliers to generate significant SSCI scores. This traces to the large quantities of radioactive cobalt they must stockpile for shipment. Sales and re-sales (by first owners) of sources present an area of concern. The SSCI scores for both industrial irradiator sources and teletherapy sources are a little under 6, which is driven by the large commerce in these sources. Radiography sources also score as very significant concerns, because there are so many buyers world-wide it would be hard to preclude a fraudulent purchase. Blood irradiators also score just above 5, with potential concerns about re-sale contributing to the score. The transportation stage appears to present some major concerns, especially regarding the frequent shipments of large quantities of Cobalt-60. The scores for industrial irradiators and teletherapy sources constitute red flags. Three other transportation scores hover near 5, making them significant concerns. The radiography sources and the well-logging sources tend to be well-traveled, exposing the sources to theft.

The SSCI scores for several of the users are high, probably because most of the sources are currently in the hands of the users. The teletherapy units score very high-approaching 7- and this is far from surprising. Regardless of the good intentions, the placement of several thousand teletherapy sources in third-world hospitals has resulted in a major RDD vulnerability. Three other users rate SSCI socres just above 6 for different reasons. The industrial irradiators have huge inventories of cobalt-60, so despite the challenges in stealing such sources, they remain a major concern. The radiography units are almost everywhere, and they are often stolen while stored in the back of pickup trucks (that are stolen). The blood irradiators are big and used in relatively open hospitals. Three additional user facilities score between 5 and 6, including the RTGs, research irradiators, and well-logging sources. Of the users, only the obsolete seed irradiators fail to score in a region of concern!

Of the disused sources, only the RTGs score above 6, mostly because there are fewer disused sources than sources in use, and because disused are often located near the sources in use. Unfortunately, RTG sources are used under vulnerable conditions, and there are many disused RTG sources. The only disused source to score between 5 and 6 is the well-logging source, largely because of the americium. There is a cluster of disused sources just below 5 that should be noted. As long as few waste disposal or consolidation sites are available, the number of disused sources will increase greatly over the next decade or two.

Orphaned sources have received great notoriety because of their glaring vulnerability. However, there are only two that generate high SSCI scores. The seed irradiators score over 6, because they are large and often located in highly vulnerable locations. Orphaned RTG are less common than their disused cousins, but they have been known to turn up in very remote locations. These score between 5 and 6 on the SSCI scale. It is noteworthy that the only two large orphan sources of major concern are in the Former Soviet Union.

Neither waste consolidation sites nor waste disposal sites generate high SSCI scores at this time, mostly because they don't yet contain that much source material. However, as more disused sources are moved to these locations, the SSCI scores will move up into regions of concern.

Thus, the RDD risk reduction priorities implied by Figure 5 are as follows:

1 Transportation of Cobalt-60 sources
2 Teletherapy Source User Facilities (Hospital Cancer Wards)
3 Disused and Orphaned RTGs
4 Orphaned Seed Irradiators
5 Industrial Irradiators, Blood Irradiators, and Radiography Sources in Use
6 Sales and Re-sales of cobalt-60 sources and radiography sources
7 RTG, Research Irradiator, and Well-Logging Source Users
8 Disused Well-Logging Sources
9 Sales and re-sales of radiography sources and blood irradiators
10 Transportation of radiography, well-logging, and blood irradiator sources

As stated before, the uncertainties in the numbers behind Figure 5 suggests that items could slide up or down the priority scale a few notches. In addition, several types of disused sources will creep up in priority over the next few years if the waste disposal log-jam does not ease.

VI. OPTIONS & IMPACT ASSESSMENTS

The groupings of options in the sections that follow are according to which parties can take actions. The first set of options could be completed by security specialists, if they are provided sufficient technical support. Similarly, the second set of options is properly the domain of governmental and regulatory bodies, again with appropriate technical advice. Finally, the third set of options could only be implemented by the radiological source producers, suppliers, and users, against with some support from technical experts.

Recovering Sources and Improving Security

Regarding the first group of options, it would not be difficult to recover many disused sources, and with a little more effort one could find many of the orphan sources. The challenge would be to consolidate these sources until they can either be recycled or disposed of permanently. The third and fourth items on the priority list, RTGs and seed irradiators, are located primarily in the former Soviet Union, so an effort focused on that part of the would could have a significant impact. The eighth item on the priority list requires focusing on the locations where the three major oil exploration companies accumulate their disused sources. Some, perhaps all, of these locations are in the U.S. and other western countries. With respect to physical security upgrades, the SSCI analysis summarized in Fig. 5 can be used to focus the efforts on maximizing the risk reduction. For example, 6000 teletherapy centers scattered in hospitals around the world are a major concern.

In analyzing this group of options, we assumed that, in most cases, half of the disused and orphan sources are transferred to waste consolidation sites, and that security at most user facilities is improved by a factor of 2 and at the average waste consolidation site improved by 67% (not all sites improved). The reason for crediting only a factor of 2 improvement in security are two-fold: first we assume rapid security upgrades that would deter theft but not stop a determined foe, and second, we assume that the intended global effort would face some practical limitations and not reach all sites in all countries. Regarding the orphan sources, it is assumed the seed irradiators receive special attention, so close to 87% are recovered and secured. With respect to user facilities, no credit was assumed for improvements in security for industrial irradiators, seed irradiators, and RTGs. The impact on priority number 4, the orphan seed irradiators, would very large- falling by nearly 90% (1 order of magnitude on the log, base 10 scale). Priorities 3 and 8 are also been addressed to a degree, with 50% vulnerability reductions projected. The vulnerabilities associated with priority 2, two of the three sources in priority 5, and two of the three sources in Priority 7 have dropped by 40%. No impact was seen on priorities 1, 6, 9, and 10, and two of the source users in priorities 5 and 7 are not impacted.

International Agreements and Regulations

In order to address several of the priority items, international cooperation is imperative. There are four major areas where action is needed: disposition of used sources, transportation security, user facility security, and regulation of the commerce in sources (sales). All ten of the priority items are potentially impacted by changes in the four areas. Disposition of used sources can include recycling, waste consolidation, and waste disposal. Laws that require used sources be returned to the source suppliers would be very helpful is the disposition of used sources, as suppliers are more capable of recycling sources or managing the consolidation of used sources. International agreements can also help with the development of regional consolidation sites and possibly waste disposal facilities. Radiological sources are transported all over the world, but transportation security requirements vary. The IAEA is working to try to improve and standardize the transportation security requirements. User facility security improvements must be worked on a global basis. The teletherapy facilities alone would require a massive undertaking. The best hope regarding source security is to forge international agreements regarding the necessary security at the various radiological source facilities and provide funding and perhaps technical assistance to foreign countries needing assistance. Source suppliers do attempt to verify the purchaser before completing sales and shipping sources. However, sources must be provided in countries where political stability is dubious and regulatory authorities are almost nonexistent. The IAEA can help by managing international registries of legitimate radiological source users, and it appears to moving in that direction. The re-sale of sources is a worrisome gap in the system. International laws must be tightened to ensure that sources are not sold or re-sold to unknown parties. There may be opportunities to utilize materials controls and accountability systems on a global basis to better track the cobalt and cesium sources used in the large applications.

For this case, we assume that half of the disused and about 30% of the orphan sources are transferred to waste consolidation sites, that some sources are recycled or transferred to waste disposal sites, and that some sources at consolidation sites move to waste disposal sites. We also assume several improvements in source security, including a doubling of security at industrial irradiators, an improvement by a factor of 3 in sales security (prevent fraudulent purchases) and transportation security, a tripling in security at several types of user facilities, which also benefits the security of disused sources that are co-located, and a 67% improvement in security at waste consolidation sites. In this case, there is significant risk reduction in each of the ten high priority items, often by a factor of 3 (consistent with the assumptions). Tighter security requirements are projected to improve the transportation scores, addressing items 1 and 10. Of the user facilities, only the industrial irradiator score was not projected to improve (part of priority 5). Priorities 6 and 9 were addressed as tighter restrictions on sales reduced the likelihood of fraudulent sales. Lastly, the vulnerabilities associated with disused and orphan RTGs, seed irradiators, and well-logging sources (priorities 3,4, and 8) are reduced.

Alternate Technologies

Although improvements in physical security, used source disposition, and the international regulatory environment can reduce the RDD risks associated with the ten priority items listed in Section 5, the root cause of the problem is the widespread use of large and dangerous radiological source materials. Each case where large and dangerous sources are utilized needs to be re-evaluated to determine whether there are better options available. There are four classes of options of available, namely: replace the application with something that presents fewer concerns regarding RDD materials, replace the radioisotope utilized with something that presents a reduced concern, alter the chemical and/or mechanical form to be more dispersion resistant, and modify the equipment to better resist theft of the device and/or the radiological source material. The alternate technology options are discussed in detail in Reference 12.

For this case, we assumed a partial set of alternate technologies is implemented to the extent possible in about a decade. In terms of replacing large applications, we've assumed that 67% of the blood irradiators have been replaced by x-ray units (with the waste cesium sources either recycled or consolidated) and 75% of the RTGs retired from active use and disposed of. In terms of dangerous source materials and their hazards, we assumed that alternate forms of the cesium chloride sources and the americium-beryllium sources have been introduced through the source manufacturers and suppliers. The hazard reduction in both cases is assumed to be 40%, as derived from an assumption that the alternate material would need to reduce the vulnerability by at least half for implementation to proceed, but that replace of the original materials would be work-in progress. In terms of source security, it is assumed that enhanced gadgetry (e.g., alert and track equipment) would be added to industrial irradiators (source strength alarm), blood irradiators, RTGs, and well-logging source *sondes*. Because it would take some time for full implementation, we've assumed the improvement to be a factor of two within a decade or so. In this case, the impacts are primarily in priorities 5 and 7 through 9, especially the sources in use. By modifying the source material, the vulnerability reduction propagates throughout the life-cycles for research irradiators, blood irradiators, and well-logging sources. The reduction in the use of blood irradiators and RTGs similarly impacts the entire life-cycle. Security gadgetry brings down the risk of theft for four of the sources.

VII. INTEGRATED STRATEGY

All three of the sets of options discussed in Section VI must be pursued in order to achieve a significant RDD risk reduction. The used source recovery and physical security efforts can provide some early benefits and could be targeted on source materials that are most worrisome-especially the RTGs and seed irradiators. However, the problem is too vast and growing too quickly for such an approach to succeed by itself. The realm of international agreements and regulations is notoriously inertial, but the opportunities for instituting improvements on a global scale require widespread cooperation. Alternate

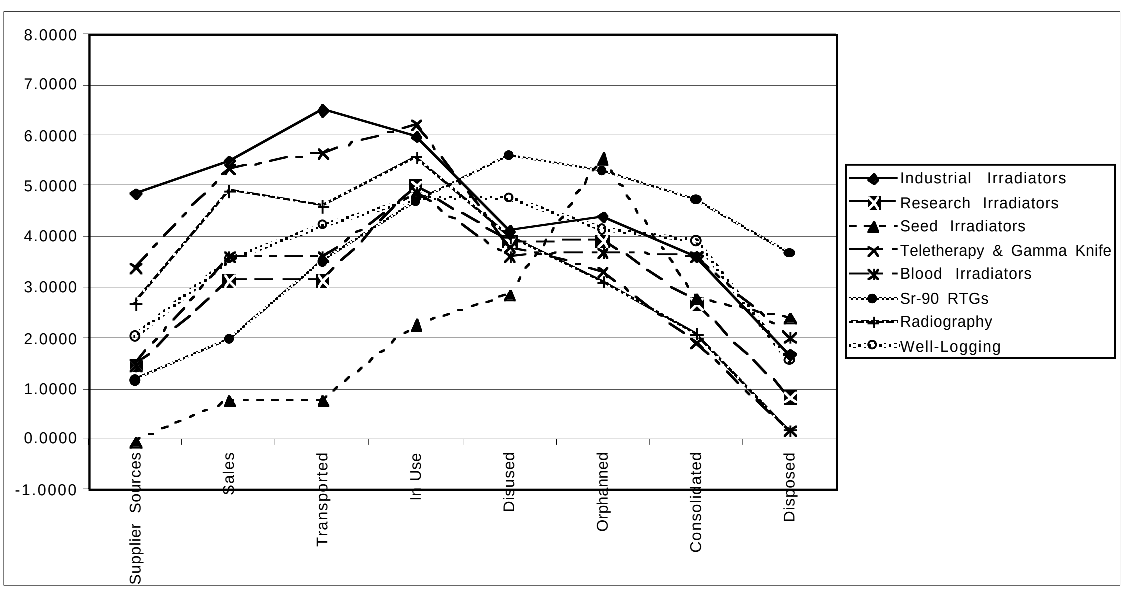

Figure 6. Projected SSCI Results for Integrated Risk-Reduction Strategy

technologies can make lasting changes, and change the vulnerabilities profoundly, but don't do much about the most immediate threats. In order to analyze this integrated approach, we combine the revised assumptions used in the three previous cases. The results are shown in Tables 3.

In some cases, overlapping impacts required some interpolations. For example, if international agreements and regulations are in parts governing the recycle or disposal of used sources, then replacement of problematic sources by alternate technologies is less likely to result in a additional disused and orphan sources. Similarly, upgrades in security due to some combination of rapid security upgrades, security upgrades mandated by international agreements, and the introduction of innovative security gadgetry would be complementary but not simply additive. The impact of the integrated strategy is shown in Figure 6.

Provided in Table 4 is the per cent change from the SSCI values in Figure 5. Note that the vulnerability increases in a few cases, but these all correspond to SSCI scores that are currently very low.

The changes in the eight SSCI scores that were originally between 6 and 7 are highlighted using solid black boxes. These include the SSCI scores for transportation and use of cobalt sources in industrial irradiators and teletherapy devices, the orphaned seed irradiators, the blood irradiators and radiography units in use, and the disused RTGs. The projected reductions in vulnerability range from 50% for the industrial irradiators to 95% for the blood irradiators. Only two SSCI scores remain above 6: the transportation of cobalt for the industrial irradiators and the teletherapy devices used in hospitals around the world. Given the fundamental nature of both concerns, the difficulty in driving down the vulnerability is not surprising.

The changes in the twelve SSCI scores that were originally between 5 and 6 are highlighted using dashes line boxes. These include the suppliers of the industrial irradiator sources, the sales of industrial irradiators, teletherapy units (and gamma-knifes), blood irradiators, and radiography sources, the transportation of blood irradiators and radiography units, the users of research irradiators, RTGs, and well-logging sources, disused well-logging sources, and orphaned RTGs. In this case, the improvements range from 50% for the suppliers of industrial irradiators to 96% for the sales and transportation of blood irradiators. Of the 12 SSCI scores originally between 5 and 6, two-thirds of those scores were reduced to below 5.

Of the SSCI scores projected to increase, only one is projected to increase above a score of 4 (consolidated RTG sources could reach 4.7). Success in reducing overall risk is very likely to move sources into the consolidation and waste sites, so these parameters bear watching.

The picture portrayed in Figure 6 and Table 4 is encouraging, as a large multi-year effort and RDD risk reduction is likely to improve the situation significantly. However, there are two disconcerting trends. First, the projected vulnerability reductions are in the range of one order of magnitude (90%), implying that 10% of a very large problem will likely remain. Second, the two vulnerabilities that remain quite high appear to be largely intractable problems. First, the shipment of large quantities of cobalt will almost certainly continue, and a review of the locations of the source suppliers and the users suggest some lengthy and vulnerable routings. Second, the teletherapy sources have been provided to hostpitals around the world and there does not appear to be any easy way to get that genie back into the bottle.

VIII. RECOMMENDATIONS

Because of limitations in this analysis and uncertainties in some of the parameters, one must be cautious in interpreting the results. On the other hand, because the analytical results range over several orders of magnitude, they tend to be very forgiving of uncertainties. As a result, it is likely that subsequent, more detailed analyses will yield results that are qualitatively similar. Assuming this to be the case, we offer the following recommendations:

- Repeat the SSCI analysis (or a variation) using more time and resources. Additional research many be able to reduce the uncertainties, especially regarding disused and orphan

Table 4 Relative change (per cent) in SSCI resulting from integrated strategy

Per Cent Change	Industrial Irradiators	Research Irradiators	Seed Irradiators	Teletherapy & Gamma Knife	Blood Irradiators	Sr-90 RTGs	Radiography	Well-Logging
Supplier Sources	-50	-70	-51	-50	-96	-92	-50	-70
Sales	-67	-80	-67	-66	-96	-90	-67	-80
Transported	-67	-80	-67	**-66**	-96	-67	-67	-80
In Use	-50	-83	-1	**-72**	-95	-94	-75	-83
Disused	-80	-91	-75	-80	-85	-75	-80	-83
Orphanned	-50	-80	-87	-60	-40	-50	-56	-60
Consolidated	-75	5	-33	-50	505	305	-4	-26

sources. A classified study using more precise numbers for hazard and security factors could also reduce uncertainties.

- Continue to aggressively develop the capability to detect and intercept attempts to transport RDDs and RDD source materials as well as the capabilities needed to respond to RDD attacks. Although the recommended course for RDD risk detection through denial of sources could reduce the vulnerability by an order of magnitude, the risk base is currently sufficiently large than the remaining 10% would still be too high.

- Balance the three classes of options and pursue each as aggressively as is practical. The source security effort can be used to address the most urgent needs, but the effectiveness is fundamentally limited. The international agreement/ regulatory infrastructure effort will likely proceed slowly, unless an RDD attack inspires a more intense effort. However, this approach can provide some far-reaching and widespread improvements in the current handling of sources. Alternate technologies can provide permanent solutions to some of the problems caused by technology choices made prior to today's global threats.

- Examine more carefully some of the high vulnerabilities that appear to be difficult to reduce. Transportation of large cobalt sources across continents exposes the sources to theft regardless of the security provided. And the location of large teletherapy sources in hospitals around the world is very troubling, despite the best intentions of those who provided life-saving technology to third-world countries.

- Focus the available resources regarding disused and orphan sources on the three primary applications of concern, namely the RTGs, the seed irradiators, and the well-logging sources. These problems are concentrated in the former Soviet Union in the first two cases and in western countries for the third case.

- Stage the approach, where some types of actions are developed and then queued for future implementation. With the current frequency of terrorist bombings, the publicity regarding the RDD threat, and the widespread availability of radioactive source materials, an RDD attack somewhere in the world is overdue. If the U.S. is prepared with a global strategy of RDD risk reduction, the best opportunity for action may develop subsequent to the first significant RDD attack.

REFERENCES

1. FERGUSON, C.D., KAZI, T., and PERERA, J., "Commercial Radioactive Sources: Surveying the Security Risks", Center for Nonproliferation Studies, Monterey Institute of International Studies Occasional Paper No. 11, January 2003.
2. STRUB, T. and VAN TUYLE, G. J., "Large Radiological Source Production and Utilization and Implications Regarding RDDs", Los Alamos National Laboratory Report LA-UR-03-5432, July 2003.
3. O'BRIEN, H. A, "Radioactive Sources in Medicine and Industry," O'Brien & Associates Report No. OB&A/OB-02-01, May 2002.
4. "Directory of Radiotherapy Centres." DIRAC. International Atomic Energy Agency and World Health Organization. (V.2000.A) (Database).
5. "TC Projects: Radiotherapy." IAEA Department of Technical Co-operation. Database. 2001. http://www-tc.iaea.org/tcweb/tcprogramme/projectsbyfacandapc/query/default.asp May 2003.
6. FRADKIN, et al, "Radioisotope Sources of Electric Power", Army Foreign Science and Technology Center Report No. OB&A/OB-02-01, May 2002.
7. PRENSKY, S.E., "A Survey of Recent Developments and Emerging Technology in Well Logging and Rock Characterizations," published in *The Log Analyst*, v. 35, no. 2, p. 15-45, no. 5, p.78-84, 1994.
8. SHLEIEN, B., SLABACK, L.A., and BIRKY, B.K., *Handbook of Health Physics & Radiological Health*, Feb 1998.
9. "C-188 Cobalt-60 Brochure." MDS Nordion. June 2001. http://www.nordion.com/master_dex.asp?page_id=122 May 2003.
10. "Code of Conduct on the Safety and Security of Radioactive Sources." International Atomic Energy Agency. December 2000. http://www.iaea.or.at/worldatom/Press/Booklets/RadioactiveSources/radioactivesource.pdf May 2003.
11. "Revised Action Plan For the Safety and Security of Radiation Sources." Board of Governors General Conference. [GOV/2001/29-GC(45)/12] International Atomic Energy Agency. 6 August 2001. http://www.iaea.org/worldatom/About/GC/GC45/Documents/gc45-12.pdf June 2003.
12. VAN TUYLE, G.J., and MULLEN, E., "Large Radiological Source Applications: RDD Implications and Proposed Alternate Technologies," Proceedings of Global 2003, American Nuclear Society Embedded Topical Meeting, New Orleans, Nov. 16-20, 2003; also Los Alamos National Laboratory Report LA-UR-03-6281.

Table 2. Parameters Used for Base Case SSCI Analysis

Number of Sources	**Industrial Irradiators**	**Research Irradiators**	**Seed Irradiators**	**Teletherapy & Gamma Knife**	**Blood Irradiators**	**Sr-90 RTGs**	**Radiography**	**Well-Logging**
Supplier Sources	120	10	1	2500	150	20	12000	2000
Annual Sales	95	7	1	2000	100	10	12000	1000
Transported	190	7	1	4000	100	10	12000	1000
In Use	190	120	1	6000	1500	800	30000	10000
Disused	1	7	1	50	10	600	50000	3000
Orphanned	0.1	3	150	5	2	100	5000	200
Consolidated	1	2	15	10	5	50	20000	2000
Disposed	1	2	10	5	1	100	10000	100

Radioactivity (Ci)	**Industrial Irradiators**	**Research Irradiators**	**Seed Irradiators**	**Teletherapy & Gamma Knife**	**Blood Irradiators**	**Sr-90 RTGs**	**Radiography**	**Well-Logging**
Supplier Sources	1200000	10000	1800	2000	5000	100000	80	18
Sales	1000000	10000	1800	1700	5000	100000	20	18
Transported	1000000	10000	1800	1700	5000	100000	10	18
In Use	5000000	10000	1800	5000	5000	100000	5	18
Disused	500000	8000	1800	1000	4000	80000	0.3	18
Orphanned	500000	7000	1800	1000	4000	80000	0.3	18
Consolidated	500000	7000	1800	500	4000	80000	0.2	18
Disposed	250000	6000	1800	500	3500	70000	0.1	18

Approx Impact (1-100)	**Industrial Irradiators**	**Research Irradiators**	**Seed Irradiators**	**Teletherapy & Gamma Knife**	**Blood Irradiators**	**Sr-90 RTGs**	**Radiography**	**Well-Logging**
Supplier Sources	10	10	10	10	10	1	10	100
Sales	10	10	10	10	10	1	10	100
Transported	10	10	10	10	10	1	10	100
In Use	10	10	10	10	10	1	10	100
Disused	10	10	10	10	10	1	10	100
Orphanned	10	10	10	10	10	1	10	100
Consolidated	10	10	10	10	10	1	10	100
Disposed	10	10	10	10	10	1	10	100

Inaccessibility (1-100)	**Industrial Irradiators**	**Research Irradiators**	**Seed Irradiators**	**Teletherapy & Gamma Knife**	**Blood Irradiators**	**Sr-90 RTGs**	**Radiography**	**Well-Logging**
Supplier Sources	100	100	100	100	100	100	100	100
Sales	100	10	100	5	5	100	1	10
Transported	20	10	100	5	5	10	1	2
In Use	50	2	10	5	5	10	1	5
Disused	25	2	2	5	5	10	1	5
Orphanned	10	5	1	10	10	20	5	10
Consolidated	10	10	10	10	10	10	10	10
Disposed	100	100	100	100	100	100	100	100

Security (1-100) *Approx*	**Industrial Irradiators**	**Research Irradiators**	**Seed Irradiators**	**Teletherapy & Gamma Knife**	**Blood Irradiators**	**Sr-90 RTGs**	**Radiography**	**Well-Logging**
Supplier Sources	100	100	100	100	100	100	100	100
Sales	10	10	10	10	10	10	10	10
Transported	10	10	10	10	10	10	10	10
In Use	100	10	10	10	10	10	1	10
Disused	3	3	3	3	3	3	3	3
Orphanned	1	1	1	1	1	1	1	1
Consolidated	30	30	30	30	30	30	30	30
Disposed	100	100	100	100	100	100	100	100

Table 3. Alternate Parameters Assuming Integrated Risk Reduction Program

Number of Sources	**Industrial Irradiators**	**Research Irradiators**	**Seed Irradiators**	**Teletherapy & Gamma Knife**	**Blood Irradiators**	**Sr-90 RTGs**	**Radiography**	**Well-Logging**
Supplier Sources	120	10	1	2500	20	3	12000	2000
Annual Sales	95	7	1	2000	20	3	12000	1000
Transported	190	7	1	4000	20	10	12000	1000
In Use	190	120	1	6000	500	200	30000	10000
Disused	0.4	2	0.5	20	5	300	20000	1300
Orphanned	0.05	1	20	2	2	50	2200	100
Consolidated	0.5	7	20	10	100	400	38000	3700
Disposed	0.2	2	136	3	50	700	15000	250

Approx Impact (1-100)	**Industrial Irradiators**	**Research Irradiators**	**Seed Irradiators**	**Teletherapy & Gamma Knife**	**Blood Irradiators**	**Sr-90 RTGs**	**Radiography**	**Well-Logging**
Supplier Sources	10	6	10	10	6	1	10	60
Sales	10	6	10	10	6	1	10	60
Transported	10	6	10	10	6	1	10	60
In Use	10	6	10	10	6	1	10	60
Disused	10	6	10	10	6	1	10	80
Orphanned	10	6	10	10	6	1	10	80
Consolidated	10	6	10	10	6	1	10	80
Disposed	10	6	10	10	6	1	10	80

Security (1-100) *Approx*	**Industrial Irradiators**	**Research Irradiators**	**Seed Irradiators**	**Teletherapy & Gamma Knife**	**Blood Irradiators**	**Sr-90 RTGs**	**Radiography**	**Well-Logging**
Supplier Sources	200	200	200	200	200	200	200	200
Sales	30	30	30	30	30	30	30	30
Transported	30	30	30	30	30	30	30	30
In Use	200	35	10	35	40	40	4	35
Disused	6	6	6	6	6	6	6	6
Orphanned	1	1	1	1	1	1	1	1
Consolidated	60	60	60	60	60	60	60	60
Disposed	100	100	100	100	100	100	100	100