



## SYSTEM ENGINEERING ANALYSIS ON THE ACTIVE DEBRIS REMOVAL (ADR) ARCHITECTURE

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**Abstract:** Throughout our space development and utilization activities since 1957, we have left many man-made objects in space, what is called, space debris. Situation of space development is getting worse as the number of space debris increases and the Active Debris Removal (ADR) is one of the technical feasible solutions to remedy space environment immediately. However the ADR is still under an early phase of concept study, though the other solutions have been in action. The purpose of this paper is to assess the ADR architecture in order to propose some solutions for making the ADR in action from the system engineering point of view. Through analyzing the ADR architecture by customer value chain analysis (CVCA) and comparing with Greenhouse Gas scheme, several clues have been found to bring the ADR in action. In addition, the ADR architecture was reviewed from legislative point of view to reveal new aspects of the ADR.

**Keywords:** space debris, mitigation, active debris removal, ADR, system engineering

### 1. Introduction

After Sputnik was launched in 1957, more than 5,000 spacecraft had been launched to Earth-centered orbits of various heights. Utilization of space has created new markets, for example, satellite communication, global positioning, weather forecast etc. and our life depends deeply on space technologies, enjoying benefits from space. For this reason, space environment

around the earth is very valuable for us.

Through our space exploration and utilization activities, we have left many man-made objects in space and they are called space debris. Definition of space debris is that "Space debris are all man-made objects, including their fragments and parts, whether their owners can be identified or not, in Earth orbit or re-entering the dense layers of the atmosphere that are non-functional with no reasonable expectation of their being able to assume or resume their intended functions or any other functions for which they are or can be authorized." <sup>1</sup>

With increasing space debris, space environment is facing danger. This was pointed out by Nagatomo mentioning the need of space traffic control because with emerging huge

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spacecraft, such as International Space Station (ISS), and the increasing probability of collision between spacecraft. He also mentioned the necessity to remove object with high collision probability.<sup>2</sup>

Based on NASA Orbital Debris Quarterly News as of January 2014, approximately 16,500 objects are orbiting near the earth and only one-fourth of these objects are operational spacecraft and the rest of them is space debris. Possibility of debris-generating is steadily increasing and we will soon face Kessler syndrome, where each collision generating space debris increases the likelihood of further collisions. (Ref. Figure 1)

As a result of the orbital debris problem, space developing community starts working on this issue diligently. The following actions are considered to be effective for restoring space environment;

- Monitoring space debris motion
- Prevention of space debris increase by spacecraft design and/or re-entry
- Removing existing space debris

As listed following, several actions regarding monitoring and prevention have been carried out. The United States Space Surveillance Network (SSN) is monitoring artificial objects orbiting Earth in order to have a better understanding of the present space environment.

Inter-Agency Space Debris Coordination Committee (IADC) has set IADC Space Debris Mitigation Guidelines in 2007 and United Nations (UN) supported that. Space developing community is following these guidelines when it designs and manufactures space objects.

On the other hand, the way to remove existing space debris is not in action. Several technologies regarding the active debris removal (ADR) are being studied and validated but the actual ADR mission is not planned.

The purpose of this paper is to assess the ADR architecture, the whole architecture including technical method, scheme for operation and funding etc. to carry out the ADR, to find out the root cause why the ADR has not been brought in action and to propose some solutions from the system engineering point of view. The first step is to review the current situation of the ADR to understand the ADR system concepts. The next step is to apply a business model concept to the ADR architecture and build a logic tree to identify a root cause. Through analyzing the ADR architecture by customer value chain analysis (CVCA) and comparing with Greenhouse Gas scheme, several clues have been found to bring the ADR in action. In addition, the ADR architecture was reviewed from legislative point of view to reveal new aspects of the ADR.

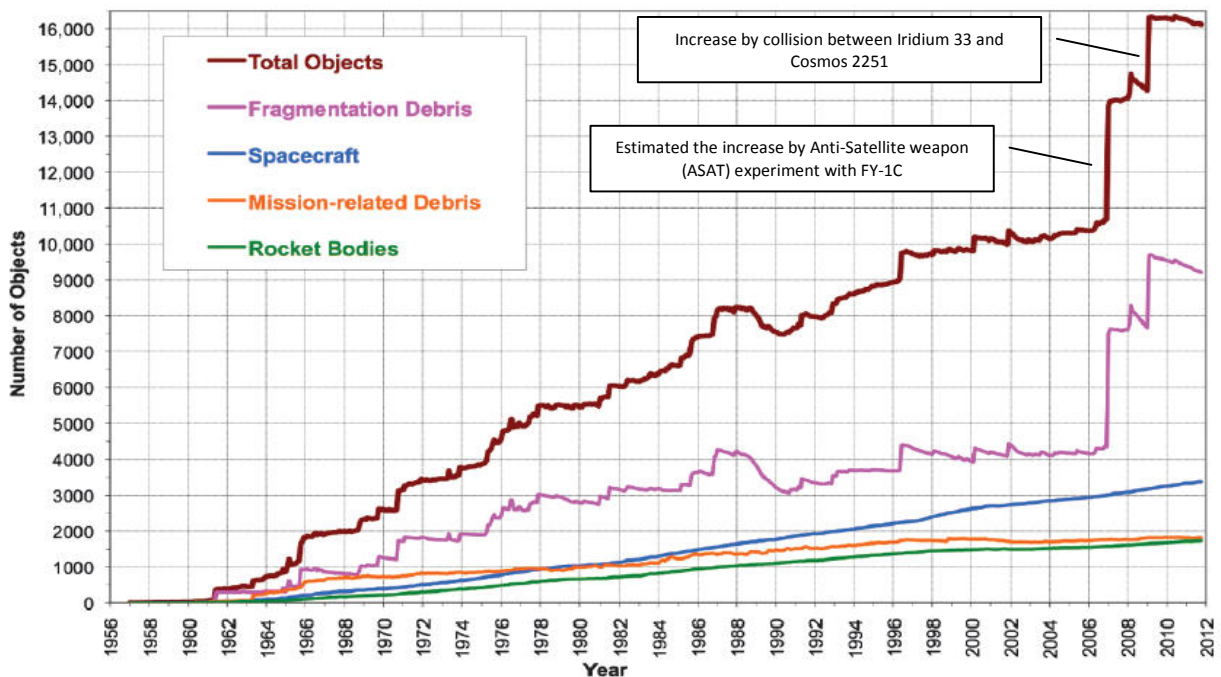


Figure 1 Monthly Number of Objects in Earth orbit by Object type <sup>3</sup>

**2. Assessment of the ADR Business Model**

By monitoring and predicting existing space debris situation, operational satellite can maneuver in order to avoid collisions with space debris. The generation of new space debris such as fragmentation due to explosions or collision with small space debris can be suppressed by following design guideline. But collisions between existing space debris are uncontrollable and will generate more space debris. To suppress collisions between existing space debris, debris removal, Active Debris Removal (ADR) is the only solution.

Due to the technical reason, the target of the ADR is large space debris, such as upper stage of rockets or non-operational satellites. The reason is that although small debris might directly bring the risk of generating space debris, they are spreading all over the space and the number is too large, so one-by-one removal of small space debris is not effective.

Based on the analysis by NASA, five large space debris removal/year starting from 2020 will suppress space debris increase. (Ref. Figure 2)

*A. Current situation of the ADR system*

From business point of view, various kinds of stakeholders will be involved in ADR activity because space development and utilization activities are international and space is handled as commons for human. But there are few positive investors who are willing to bear the ADR cost. One reason is that even though the recognition of necessity and emergency of space debris treatment is increasing in only space community, it is not common in other stakeholders. When the expected loss by space debris exceeds the life-cycle cost of spacecraft or the break-even point of spacecraft insurance, some stakeholders will be induced to invest ADR.

*B. Logic tree on the ADR*

To analyze why the ADR activity has not been promoted as business, let apply business model concept to the ADR and try to explore a root cause.

Based on Osterwalder and Pigneur, "business model describes the rationale of how an organization creates, delivers, and captures value." and they provide a tool, Business

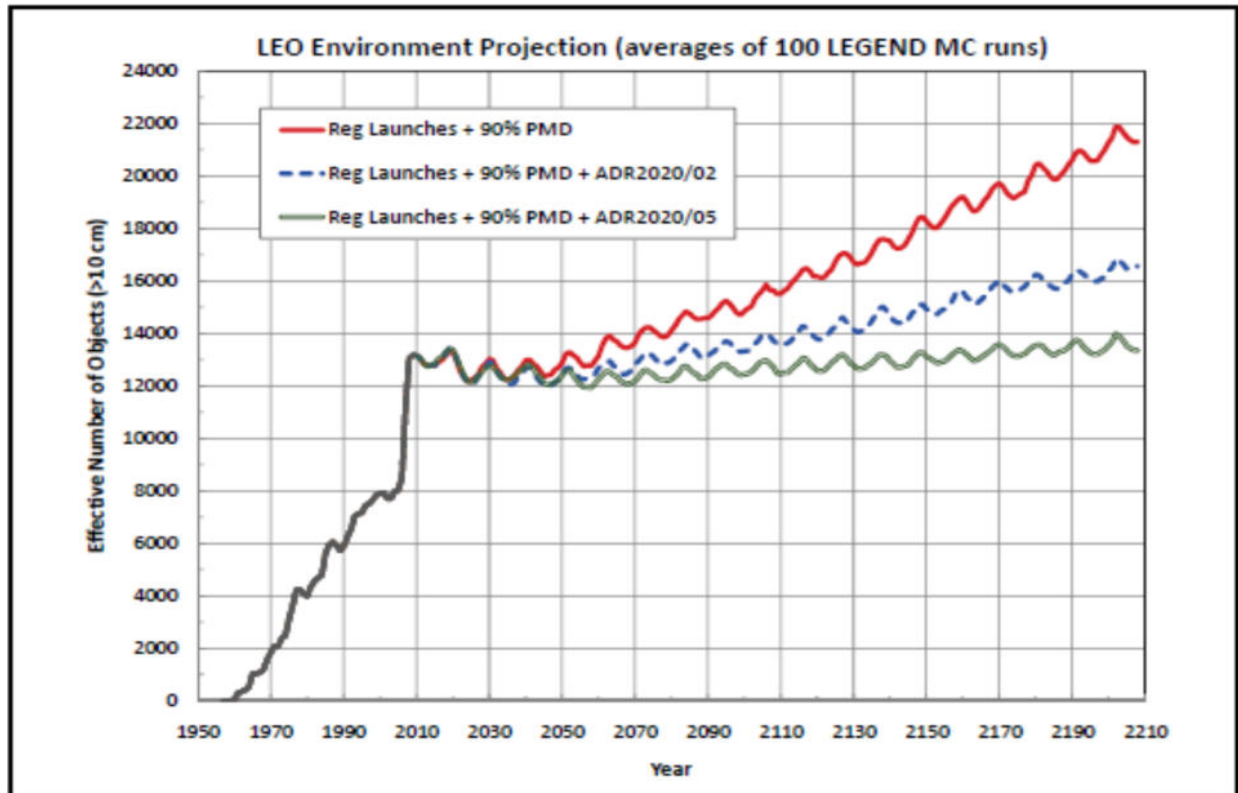


Figure 2 Estimation of debris of Low Earth Orbit <sup>4</sup>

Canvas, to design a business model. In the model, there are nine building blocks in four segments; customer, value, infrastructure and cost construction.<sup>5</sup> The followings are reviews of each item.

#### 1) *Customer Segments*

If the number of space debris is increasing and Kessler syndrome has occurred, space faring party cannot utilize space technologies and daily life of people living in civilized society is affected deeply. So in the ADR business model, the direct customer is space faring party and the indirect customer is all people living in civilized society. Space faring party is a direct customer and also can be an executor of the ADR. People in civilized society cannot make a decision to carry out the ADR because they do not notice that they are enjoying benefits from space development, although their daily life is depending on space technologies. Removing space debris is a kind of public service and people only expects public service be carried out properly. So even though people are a customer, it is better to focus on space faring party to carry out the ADR.

#### 2) *Value Propositions*

After the ADR is in action as business, space environment will be restored and space faring party can utilize space technologies steadily. The value that the ADR business brings is restored space environment.

#### 3) *Infrastructure*

##### a) *Channels*

Risk of Kessler syndrome is getting lower, space faring party can keep its space development activities and people can enjoy benefits of space technologies, then it is noticed that space environment has restored.

##### b) *Customer Relationships*

Current space faring party will carry the ADR business and also it will enjoy benefit from the ADR. It means that the ADR business will be done for its own interest. Most space faring organization and/or industries will belong to socialized nations and their people also will enjoy benefit from the ADR by utilizing space technologies but people will not notice that they are enjoying benefit from the ADR. It means that space faring party who will carry the ADR is a kind of public servant.

#### c) *Revenue Streams*

When some space agency carries the ADR, its government makes a decision to burden the ADR cost. When a private company, "customer" burden cost.

#### d) *Key Resources*

- *ADR Technologies ADR*
- *Scheme with assured expense*
- *Legislative system*

are key resources.

There is no scheme and legislative system established and they should be examined immediately. Especially who burden the ADR cost depends on the scheme and it is essential.

#### e) *Key Activities*

Key resource should be established.

#### f) *Key Partnerships*

The ADR will be an international project and partnership between space faring party is essential.

#### 4) *Cost Structure*

The ADR system will be composed of,

- *Spacecraft*
- *Launcher*
- *Ground system*

The total cost includes cost for development of each item and for operation of the ADR system, including insurance premium.

Figure 3 shows logic tree of the ADR Business Model.

### 3. **Discussions**

In this section, let discuss some blocks of the ADR business model and root causes to try to find the solution.

#### A. *Customer Value Chain Analysis (CVCA) on the ADR*

In order to investigate more deeply about customers, let analyze by Customer Value Chain Analysis (CVCA) and assuming that some organization carries the ADR, ADR Operation Organization. Figure 4 shows CVCA on the ADR architecture. Space Agency or Space Faring Party makes an order to carry out the ADR to ADR Operation Organization. Like other spacecraft development process, ADR Operation Organization makes orders to Spacecraft Launch Company, Spacecraft Manufacturing Company and Spacecraft Operation Company and also makes a contract

with Insurance Company. Space Agency and Space Faring Party offer services based on space technologies to people (Humankind/Nations), some are free and some are charged a fee. Space Agencies are under control of Government and people pay tax to Government.

CVCA on the ADR architecture shows that people are indirect customers of the ADR even though people enjoy space technologies directly. Let analyze two ADR business cases, order by a

private company and order by space agency.

When some communication operator, a private company, orders the ADR, it must order to remove specific space debris which will bring risk to its communication operation. And its cost will be managed by profit of the communication operator and the communication operator adds its cost to its fee collecting from people.

When Space Agency orders the ADR, it also orders to remove specific space debris, but it

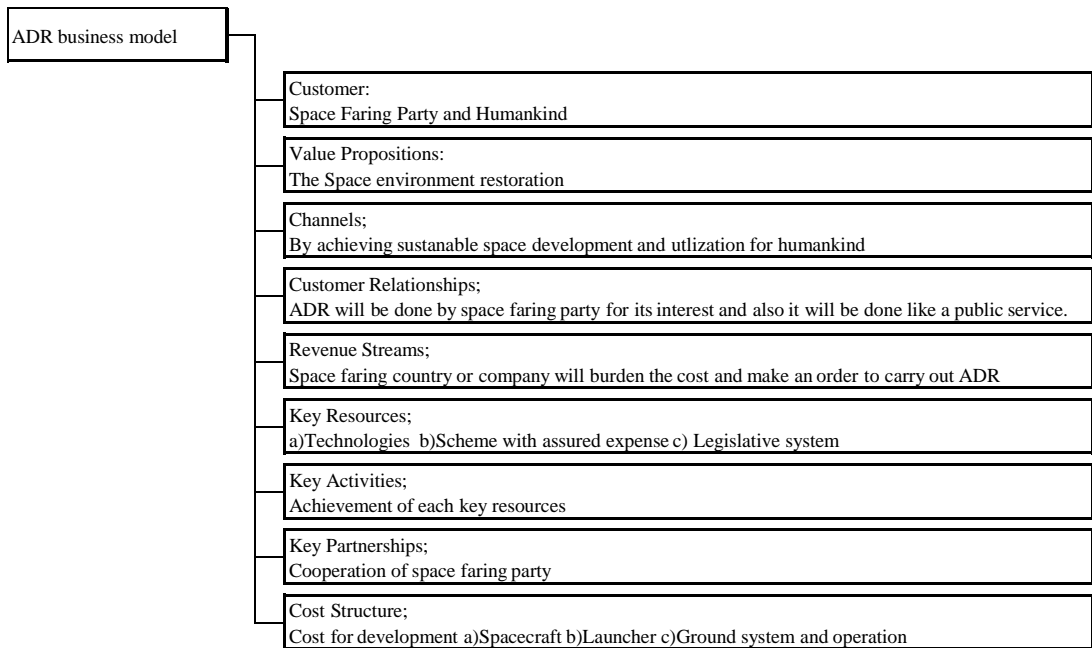
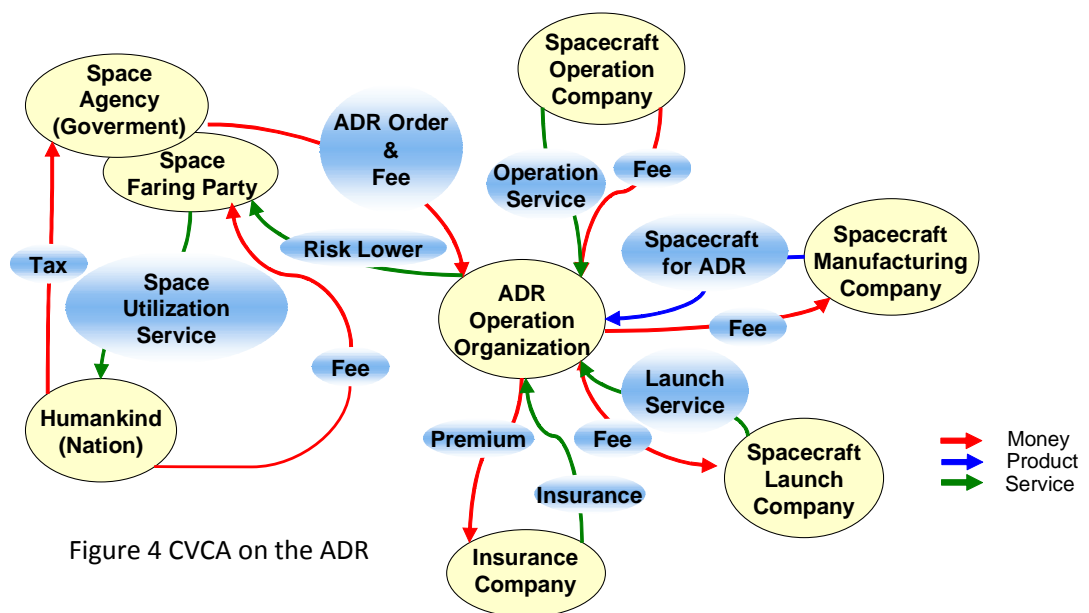


Figure 3 Logic Tree of ADR Business Model



will select space debris for the purpose of restoring space environment. For example, European Space Agency (ESA) expresses "Clean Space Initiative" and admits that Envisat "was a subject of major interest in the Space Debris and Legal session" at International Astronautical Congress in 2012. System of removing Envisat has been actually studied. So ESA's current ADR target is Envisat.<sup>6,7,8</sup> And Japan Aerospace Exploration Agency (JAXA) also has studied system for removing ADEOS which ended its operation after six months after its launch in 1996.<sup>9,10</sup> These satellites are not immediate risk to some specific satellite, but removing them will lead to restore low earth orbit (LEO) environment. The expense of Space Agency is supplied by Government budget, tax. In either case, people will burden cost of the ADR, even though they are indirect customer. In order to get people's consensus that tax is used for ADR, debris risk recognition should be widely spread.

*B. Comparison with Greenhouse Gas*

Same as space debris, greenhouse gas is risk to humankind. It will cause global warming, change in some climate extremes, reduce in snow and ice, change in global mean sea level rise and threat an ecological system.

Under United Nations Framework Convention on Climate Change (UNFCCC), nations are

coping with a greenhouse gas issue. Although its activities are criticized not be effective to achieve the final goal, yet there is an international consensus that people should face with a greenhouse gas issue and several actions are carried out to reduce a greenhouse emission. Figure 5 shows the logic tree of reducing greenhouse gas emission business model. Comparing Figure 3 and Figure 5 shows that the major difference is customers are involved in the model indirectly. In the ADR business model, people (Humankind) are enjoying the value indirectly whereas in reducing a greenhouse gas emission business model, people are paying its cost by buying goods/devices to reduce emission of a greenhouse gas.

One of the famous activities of UNFCCC is Kyoto Protocol. It induced developing nations involved in reducing a greenhouse gas emission business by applying some mechanisms, International Emissions Trading (IET), the Clean Development Mechanism (CDM), and Joint Implementation (JI) etc. Although their merits and demerits are discussed, they let developed nations and developing nations be involved in reducing a greenhouse gas emission business because they thought there is a business chance.<sup>11</sup> These mechanisms work as incentive in reducing a greenhouse gas emission

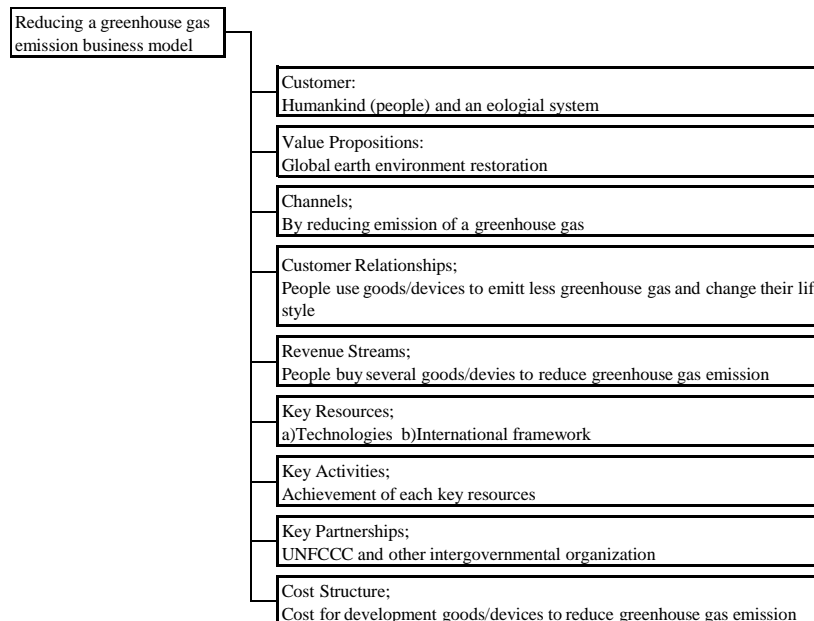


Figure 5 Logic Tree of Reducing emission of a greenhouse gas

business model.

So if there is some mechanism which works as incentive in the ADR business model, it would bring a chance to the ADR be carried out. And it is expected that the mechanism let people (customer) be directly involved in the ADR business because the scheme will secure cost allocation.

*C. Scheme with assured expense*

As mentioned above, the ADR activity can be a kind of a public service. And in ADR business model, customer is Humankind and space debris are orbiting in space where it is handled as commons, because in Outer Space Treaty, it says that "outer space is not subject to national appropriation by claim of sovereignty, by means of use or occupation, or by any other means."<sup>12</sup>

So in order to carry out the ADR, some International Operation Organization should manage the ADR and it will select which space debris to be removed, order the ADR mission and manage the ADR cost.

Selecting space debris will depend on the two factors; one is space debris' risk potential and the other is who burdens the ADR cost. Whereas it is preferred to remove the specific space debris with high risk of collision, if the ADR cost is not guaranteed, then the ADR would not be carried out. So cost allocation is a very important factor in the ADR business.

There are several cases of the ADR cost allocation and categorized in three types.

*1) Who requests the ADR will burden cost*

It seems very reasonable that who wants to remove space debris will pay the ADR cost. In

this case, the communication satellite operators will request the ADR to prevent collision between their operating satellite and space debris. Most of communication satellites are orbiting in geostationary earth orbit (GEO) and removing space debris near GEO is thought to be not so effective to prevent Kessler Syndrome because collision probability of GEO space debris is not so high. And because the communication satellite operators think the risk of collisions is not so imminent right now, they do not feel the need of the ADR. In order to let involve these communication satellite operators in the ADR business, it is necessary to make them recognize the necessity of removing space debris in LEO and the International ADR Operation Organization require additional cost to remove space debris not only in GEO but also in LEO.

*2) Who led the current space situation will burden cost*

It also seems reasonable that who owns or has produced space debris burdens the ADR cost. Table 1 shows the current space debris numbers registered with each nation. In this case, there are two ways to allocate the ADR cost; one is to allocate cost to the registered nation of the specific space debris to be removed, the other is that all nations of current space faring party burden the ADR cost. The former way spreads sense of unfairness among space faring party and each nation will be against to carry out the ADR requesting the valid reason why its registered space debris should be removed. In the latter way, allocation ratio will be decided based, for example, on the numbers of registered space debris or the risk of registered space debris. Then, same as the former way, each space faring nation will request the valid reason for its cost allocation.

*3) Who will enjoy benefits from space technologies will burden cost*

In this case, for example, all nations that had ratified will burden the ADR cost and it is very similar with activities under UNFCCC. UNFCCC states that Parties should act to protect the climate system on the basis of "common but differentiated responsibilities", and that developed nation Parties should "take the leading addressing climate change. It

Country/ Organization	Payloads	Rocket Bodies & Debris	Total
CHINA	155	3609	3764
CIS	1439	4737	6176
ESA	46	45	91
FRANCE	58	442	500
INDIA	53	119	172
JAPAN	124	82	206
USA	1174	3787	4961
OTHER	666	119	785
TOTAL	3715	12940	16655

Table1 Satellite Score Box As of 1 Jan. 2013 cataloged

requires that developed nations be willing to commit financial resources and transfer of technology to developing nations because the extent to which developing nations will depend on the effective implementation by developed nations."

In the ADR case, nations supporting the International ADR Operation Organization are required to commit the ADR on the bases of "common but differentiated responsibilities", then nations that are only enjoying space technologies, for example GPS and/or satellite-based telecommunication, and not operating satellites are required to commit the ADR. And current space faring nations are required to lead the ADR by introducing space technologies to developing nations. To achieve this case, it is necessary to let many nations support the International ADR Operation Organization concept.

Considering the three ADR cost allocation cases, it is necessary for the International ADR Operation Organization to establish the fair criteria

to select space debris to be removed  
to establish international consensus  
about ADR and its cost allocation

#### *D. Legislative system*

Regarding the ADR architecture, there have been several legal issues identified in Space Law because the ADR will be an international activity in space which is handed as common to Humankind. Committee on the Peaceful Uses of Outer Space (COPUOS) of UN have five major treaties as Space Law and their distinct feature is each nation should be responsible in its nation's space activities, even if it was done for commercial purpose.<sup>13</sup>

Let investigate whether we could accuse a nation regarding space debris registered with that nation and it seems difficult to accuse a nation because of the following reasons;

When a collision occurs in space, it is difficult to identify which is a wrongdoer side and a sufferer side because we can only draw an inference from a conclusive evidence.

Leaving space debris as it is not accused because the situation would not lead a loss and moreover there is no verified technology to

remove space debris. Technologies regarding the ADR are under study as mentioned above.

In case of violating design guideline which UN has established will let a spacecraft become space debris, we cannot accuse a nation because there is no authority of accusation based on the design guideline.

It is assumed that when the ADR technologies would have been verified, the international consensus to accuse a nation will be formed regarding leaving space debris as it is and violating design guideline.

Then let assume the situation when the ADR technologies are verified. When the International ADR Operation Organization selects specific space debris to be removed based on some criteria and its selection is against to a nation's interest, that nation will plead insisting its ownership. In case that the selection by the International ADR Operation Organization is admitted by a nation and during the ADR mission, some loss is caused, then the issue is who is responsible for that loss. Even if specific space debris causes a loss, removing that space debris from its orbit is triggered by the ADR mission, then it is natural that the International ADR Operation Organization is responsible for that loss. Then it is necessary to prepare some fund to compensate the loss.

#### **4. Conclusions**

Even though the necessity of the ADR is recognized by space faring nations, the ADR business cannot be carried out because of lack of analysis on ADR architecture.

This paper made an attempt to do several assessments regarding the ADR architecture by CVCA, comparing with Greenhouse Gas Issue and logic tree. And legal issues are discussed. The result gave some clues that the current ADR business should be considered.

International consensus of risk caused by space debris should be widely spread. Along with the ADR technologies being verified, it is necessary to establish fair criteria to select space debris to be removed and consensus to allocate the ADR cost. Some incentive mechanisms are essential to cost allocation.

The verification of the ADR architecture with implementing these factors will be the future work.



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