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LAUNCH SYSTEM HAZARD STUDY: METHODOLOGY AND LESSONS LEARNT AFTER 5 YEARS OF APPLICATION

D. Delorme(1), A. Biard(2)

(1) CNES/DLA, 52 rue Jacques Hillairet Paris 75612 Cedex 12, david.delorme@cnes.fr
(2) CNES/DLA, 52 rue Jacques Hillairet Paris 75612 Cedex 12, arnaud.biard@cnes.fr

ABSTRACT

Risk management for new launch vehicles issuing from different origins and original industrial organizations, was a great challenge. In order to assess risk for launch operations, a specific type of risk analysis from take-off along the flight is performed. This analysis is called Launch System Hazard Study.

The method is a classical one for high-risk industry, for which all the risks shall be assessed and mastered. These classical studies identify the hazard on ground and establish the risk mitigation to reduce the risk occurrence (prevention measures) and/or to minimize the effect (correction measures), like in particular the evacuation of the hazard zone.

One of the main differences between the risk industry and the launch vehicle is that the latter is a moving source of hazard, which can be very large and reach many places on Earth or in orbit.

More precisely the hazard study is an analysis that includes a description of all the hazards related to the operation in nominal and accidental operating situations, whether their cause is internal or external. The study specifies the nature and scope of the possible consequences of all these operating situations. When dealing with elements of the launch vehicle which are returned or which fall back and are liable to reach the ground, the study presents the components of these elements, stating their dimensions, masses and materials used.

Moreover the study must present an exhaustive analysis of the causes and consequences, as well as the probabilities of the critical events. The mitigations are also defined, if necessary.

Since 2010, each new development of a European launch vehicle required a hazard analysis. The lessons learnt consisted in the adaptation of the methodology not only to the scale of the launch system evolution, but also to the different phases or type of development, from a complete launch system to an adaptation for a specific mission.

To allow this flexibility, the challenge was to simplify the analysis, without losing from the accuracy and the completeness point of view. The benefit of this approach is to have a more efficient methodology, more widely usable and fruitful all along the development, to anticipate and optimize the mitigation measures.

1. INTRODUCTION

French Space Operation Act (hereafter FSOA) and associated regulations came into force on 2010, December 10th. Their goal is to establish the legal safety of each space operator. They aim at ensuring the space activities’ technical risks mastery, considering in particular third party risks. These third party risks are mainly the consequences of damages to persons, to public health, to belongings and to environment that can occur during the space operation. According to the regulatory frame, the hazard study is the method to be applied in order to identify and mitigate those risks.

CNES, French Space Agency, has 2 types of missions: the first one is to develop and maintain the expertise in the methodologies to identify and mitigate the risks. The second one consists in verifying for the French government the accuracy of the operator demonstration of the launch operation compliance with the regulations.

For European launch systems, the hazard study is begun as soon as possible in the development plan. Today, after several developments, some improvements due to lessons learnt have been implemented.

2. FSOA TECHNICAL REGULATION

In accordance with II.2°c) of article 1 of the FSOA decree of 9th June 2009 [A1], the launch operator carries out a study of the potential hazards involved in the planned space operations.

To do so, in accordance with Article 7 of decree concerning Technical Regulation [A3] (hereafter TR), the launch operator must perform a Launch System Hazard Study.
ing situations, whether their cause is internal or external.

The study specifies the nature and scope of the possible consequences of all these operating situations. When dealing with elements of the launch vehicle which fall back and are liable to reach the ground, the study presents the components of these elements, stating their dimensions, masses and materials used.

The launch operator must therefore:

• demonstrate compliance with the quantitative requirements (cf. article 20 of TR [A3]), with regard to the collective casualty risk;
• evaluate the effects of any accidents on public health and the environment.

This study must cover the following events, in the conditions stipulated in chapter 3 of [A3]:

• damages linked to fall-back of elements designed to separate from the launcher;
• damages linked to controlled or uncontrolled reentry of launcher elements placed in earth orbit;
• damages linked to failure of the launch vehicle;
• collision with manned space objects, for which the orbital parameters are precisely known and available;
• damages linked to explosion of a stage in orbit;
• collision with a celestial body.

The study must present an exhaustive analysis of the causes and consequences, as well as the probabilities of the aforementioned critical events. The risk reduction measures such as to comply with the technical requirements of the Technical Regulation (Chapter 3 of [A3]) are listed in the risk management plans laid out in the article 9 of [A3].”

3. GENERAL PRINCIPLES OF THE HAZARD STUDY METHODOLOGY

In answer to TR article 7 the methodology described hereafter has been proposed by CNES and is described throughout the “Guidelines of Good Practices” cf. Article 54 of [A3].

This study includes a description of all the hazards related to the operation in nominal and accidental operating situations, whether their cause is internal or external to the Launch System.

The study specifies the nature and scope of the possible consequences of all these operating situations. When dealing with elements of the launch vehicle which fall back and are liable to reach the ground, the study presents the components of these elements, stating their dimensions, masses and materials used.

The study must present an exhaustive analysis of the causes and consequences, as well as the probabilities of the critical events at the origin of these hazard scenarios. The mitigation measures are listed in the risk management plans.

Main topics of the hazard study are the following:

✓ Description of the space operations, procedures and systems;
✓ Hazards identification;
✓ Identification of the feared events and their effects;
✓ Eligibility criteria for risks;
✓ Risks management (mitigation);
✓ Synthesis and conclusion: Synthesis tables & Mitigation risks measures list.

Note: The feedback from previous launches is taken into account in each part of the hazard study.

Five years after the first hazard studies performed in the scope of the different European launch systems, the general methodology as above-mentioned described in the “Guide of Good Practices” is still relevant. Nevertheless some improvements have been implemented.

4. IMPROVEMENTS OF THE METHODOLOGY

The first launch system hazard studies performed after the FSOA came into force had some weaknesses to be improved.

The analysis table containing the justification of the acceptability of the risks was a bit complex and contained up to 22 columns. It generated the following disadvantages:

• The study was too theoretical and difficult to read and be understood by people who are not usually in charge of risk management
• The logic of acceptability was uneasy to follow, as the requirements that come from the different TR articles are not solely quantitative
• The traceability to the reference of the detailed technical analyses used as input were difficult to follow
• This complexity had also the disadvantage to make uneasy and very time consuming the evolution of the study in case of evolution of launcher mission and hardware configuration. The hazard study format was also not very well adapted to assess the impact of a new development or a specific mission.
The objectives of the hazard studies improvements aimed at making the final document more synthetic and more readable, with the strong constraint to lose neither reliability, nor exhaustiveness.

The expected benefits are:

• An enlarged diffusion and a better appropriation of the safety issues by the different actors involved in the project, and not just a document dedicated to the safety experts;
• A better understanding of the overall logic of the risk management for each potential effect thanks to a higher synthetic level;
• An improvement for the traceability of the referencing of the detailed technical analyses which were performed in the scope of the management process of the risk mitigation;
• An easier assessment of the impact of a launcher definition or mission evolution, like hardware or trajectory change.
• A better appropriation of the hazard study by the project team for a better anticipation and piloting of the risks throughout the development program.

4.1 Description of the space operations, procedures and systems;

In the hazard study the general description of the overall launch system can be limited to the key elements linked to safety (i.e. the main hazard situations), as the reader can have access to a more general description in other launch system documentation, like the definition file or the justification file.

With respect to the safety aspects, the flight domain can be described by the successive flight phases:

• Close range zone: authorized envelope for launch vehicle movements during the first moments of flight. The close-range zone ends no later than the radio horizon or the range limit of the CNES/CSG remote-control and neutralization station, according to the Decree regulating the operation of the Guiana Space Center facilities (DRO) cf. [A4].
• Far field zone: this phase succeeds the previous one following either the loss of the neutralization capacity (ground or on-board) of the launch vehicle, either the moment at which the impact zone is tangent to the territorial waters of the first State encountered along the nominal trajectory (cf. TR article 18). It ends when the launch vehicle is in orbit.
• Fall-back of the element designed to separate to the launcher: during the close range or far field zone, such elements must not impinge on the territory, including the territorial waters, of any State, without its agreement. (cf. TR article 23).
• Orbital phase: Orbital flight and maneuvers of the launcher or elements of the launcher, including in-orbit life, passivation and disposal maneuvers (cf. TR article 21).
• Reentry phase: phase which starts with the reentry of the space objects in the terrestrial atmosphere and ends when the debris reach the ground, in the scope of a controlled or not controlled reentry (cf. TR Article 20).

Regarding the hazard study the main parameters to be described are:

• The flight sequence of the launcher events linked with those latter safety topics
• The ground track of the instantaneous impact point, as it can be seen on Figure 1 below
• The nominal fallback areas of elements designed to separate from the launcher and deorbit impact area if any.

![Figure 1: Ground track of impact point](image)

An example of such flight sequence for an Ariane 5/ES mission is shown on Table 1.

<table>
<thead>
<tr>
<th>Event</th>
<th>Close range</th>
<th>Far field</th>
<th>Orbital flight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Event</td>
<td>Lift-off</td>
<td>Start of orbital flight</td>
<td>Start of mission = stop of avionics</td>
</tr>
<tr>
<td>Booster jettisoning: fallback in Atlantic</td>
<td>Booster jettisoning: fallback in Atlantic</td>
<td>Start of orbital flight</td>
<td>Start of mission = stop of avionics</td>
</tr>
<tr>
<td>Fairing jettisoning: fallback in Atlantic</td>
<td>End of visibility of the neutralization remote control</td>
<td>Exit of A area (perigee &gt; 2000km)</td>
<td>Start of mission = stop of avionics</td>
</tr>
<tr>
<td>Cross of ISS orbit (altitude = 400 km)</td>
<td>Start of orbital flight</td>
<td>Shutdown of upper stage 2nd boost</td>
<td>Start of mission = stop of avionics</td>
</tr>
<tr>
<td>Shutdown of upper stage 1st boost</td>
<td>Ignition of upper stage 1st boost</td>
<td>Ignition of upper stage 2nd boost</td>
<td>Start of mission = stop of avionics</td>
</tr>
<tr>
<td>Exit of A area (perigee &gt; 2000km)</td>
<td>Start of orbital flight</td>
<td>Shutdown of upper stage 2nd boost</td>
<td>Start of mission = stop of avionics</td>
</tr>
<tr>
<td>Ignition of upper stage 1st boost</td>
<td>Start of orbital flight</td>
<td>Ignition of upper stage 2nd boost</td>
<td>Start of mission = stop of avionics</td>
</tr>
<tr>
<td>Separation of first set of payload</td>
<td>Ignition of upper stage 2nd boost</td>
<td>Separation of second set of payload</td>
<td>Start of mission = stop of avionics</td>
</tr>
<tr>
<td>Separation of second set of payload</td>
<td>Separation of second set of payload</td>
<td>Separation of first set of payload</td>
<td>Start of mission = stop of avionics</td>
</tr>
<tr>
<td>Start of passivation of upper stage</td>
<td>Separation of first set of payload</td>
<td>Separation of second set of payload</td>
<td>Start of mission = stop of avionics</td>
</tr>
<tr>
<td>End of mission = stop of avionics</td>
<td>Separation of second set of payload</td>
<td>Start of passivation of upper stage</td>
<td>End of mission = stop of avionics</td>
</tr>
</tbody>
</table>
4.2 Hazard Sources identification

Two classes of danger source must be addressed: external and internal.

The external danger sources are linked to the launcher environment:

- Thunderbolts;
- Winds on the launch pad;
- Winds in altitude (light fragment);
- Winds on coasts (toxicity impact);
- Rain / temperature drop / frost;
- Excessive electromagnetic fields;
- Outer space conditions (temperature, vacuum, ...);

The external danger sources linked to humans are intentionally not considered in the hazard study:

- Malicious acts, sabotage or terrorism affecting the flight, but are subject to special measures in Guiana Space Center.
- Boats, aircraft, manned spacecraft or unmanned space objects are not considered as danger, but as “targets”.
- The dangers associated with the preparation of launch are managed under other regulations (occupational safety, ICPE, ...).

Note: natural disasters (geological or hydrological or biological phenomenon, wildfire, severe turbulence and off-specification) were not selected because they are considered very unlikely in Guyana or irrelevant in our study.

The internal danger sources are the launcher failures, which must be identified through usual dependability analyses, as launcher risk analysis and failure mode analysis, for the aim of achieving the exhaustiveness of the identification of danger sources.

4.3 Potential victims of mission anomalies

Four types of potential targets of incursion are identified in case of mission anomalies:

- Humans on Earth (land, air (planes), sea (boats)) and public health;
- Man-rated flights (International Space Station or other man-rated flights whose parameters are well known and available);
- Properties;
- The atmospheric environment (land, air, sea) and the outer space environment (specific requirements applicable for protected LEO and GEO zone cf. TR article 21, for celestial bodies, cf. TR article 26).

4.5 Acceptability criteria

For each effect the involved applicable articles of the TR or DRO are identified to define the relevant acceptability requirement.

These requirements depend of the considered flight phase, and are based on both quantitative and qualitative criteria, as:

- Qualitative failsafe/failsafe requirement at the launch system level for the close range zone and deterministic approach to exclude any hazard in the protected area, whether mechanical, thermal or toxic;
- Quantitative requirement for the collective risk of causing at least one casualty of $2 \times 10^{-5}$ for the lift-off up to the orbital flight, and $2 \times 10^{-5}$ for the reentry phase;

Chapter 3 of the TR contains other specific technical requirements for the launch operations. The acceptability criteria are specific to each article, and therefore the generic eligibility for Humans and Environment considered in the first hazard studies, led to a higher abstraction level that harmed the readability.

As an improvement, the acceptability of the effects on the target is now strictly stated with regards to the criteria expressed in the concerned articles of the TR.

4.6 Identification of the feared events and their effects

The Feared Events (FE) are the phenomena which are potentially feared by the targets. The generic list of FE comes directly from the art. 7 of the TR (cf. §3).

From the launch system risk analysis and following a flight phase analysis, the different effects resulting from launcher failures which potentially lead to the FE are identified. All these cases are gathered in a synthesis table (see Table 2) containing the following information:

- Hazard source: origin of the hazard, coming from external environment, or from internal launcher failure;
- Feared Event: generic feared event coming from the art 7 of TR;
- Flight phase: part of the flight involved in the effect (close range, stage fallback, far field, orbital flight, reentry);
- Effect: wording of the effect;
- Damage class: severity of the worst feared consequence on the target.
For a dedicated mission, about twenty different effects are identified. As an illustration, the different effects analyzed for a particular mission of Ariane 5 are:

- Launcher fallout or explosion following lightning impact on an in-flight launcher in close range
- Launch pad destruction due to launcher drift following excessive ground wind at lift-off.
- Launcher fallout or explosion following excessive altitude wind in close range
- Nominal fallout of stage (boosters fairing, first stage)
- Launcher fallout or explosion after electrical failure due to radiation environment in far field or orbital flight
- Collision of the launcher or elements of the launcher with an aircraft
- Launcher fallout or explosion due to internal failure in close range
- Untimely separation of elements designed to separate from the launcher
- Non-nominal fallout of elements designed to separate from the launcher
- Creation of maritime wrecks leading to potential collision with a boat
- Launcher fallout or explosion due to internal failure in far field leading to fallout of debris on inhabited land
- Fallout of the upper composite following an underpropulsion of the lower composite on inhabited land
- Fall out or explosion of the upper composite following an underpropulsion resulting of a bad ignition of the first booster, on inhabited land
- Explosion of the upper composite following a bad ignition of the first boost leading to debris in orbit or collision of fragments with inhabited space stations
- Collision with the inhabited space station during the launch phase
- In-orbit explosion due to internal failure of the upper composite before mission disposal leading to creation of in-orbit debris and chain reaction (Kessler syndrome) or loss of human life in inhabited space stations.

For each effect, a synthesis sheet is emitted (see Table 3) to summarize the treatment logic, the analyses which have been performed, the associated identified mitigation plan, implemented in development and to be performed in production, as well a clear status identifying the acceptability by the project or the identification of the analyses which remained to be done.

### Table 3: Effect Synthesis Sheet

<table>
<thead>
<tr>
<th>Feature</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flight phase</td>
<td>Concerned flight phase (cf. flight sequence)</td>
</tr>
<tr>
<td>Hazard</td>
<td>Identification of the origin of the Hazard</td>
</tr>
<tr>
<td>Target</td>
<td>Identification of the target</td>
</tr>
<tr>
<td>Scenario and effect</td>
<td>Description of the feared scenarios and events</td>
</tr>
<tr>
<td>Feared event probability</td>
<td>Probability of causing a loss of human life, permanent invalidity or irreversible harm to public health, if the feared event occurs. This is the probability before and after the mitigation measure is effective</td>
</tr>
<tr>
<td>Reference of FE</td>
<td>Identification of the feared event</td>
</tr>
<tr>
<td>Regulation Requirement</td>
<td>Identification of the concerned requirement TR or DRO</td>
</tr>
<tr>
<td>Mitigation action</td>
<td>Implemented mitigation measures which allows to make acceptable the consequences of the Feared Events with respect to the regulatory requirements</td>
</tr>
<tr>
<td>Lessons learnt</td>
<td>Lessons learnt from other programs, when available</td>
</tr>
<tr>
<td>Project justification</td>
<td>Justification synthesis and reference of detailed notes performed by the development project team.</td>
</tr>
<tr>
<td>Exploitation actions</td>
<td>Identification, if any, of the activities to be done for each flight by the launch system operator in order to mitigate the associated risks</td>
</tr>
<tr>
<td>Status</td>
<td>Identification of what still to be done (project analyses and documentation) for the final demonstration of the acceptability in development and Acceptability status: green = acceptable risk, red = non acceptable risk</td>
</tr>
</tbody>
</table>

International Association for the Advancement of Space Safety
4.7 Mitigation

For each feared event, mitigation measures must be defined to make it acceptable.

In the close range zone, the key mitigation measure is the ability to neutralize the launcher from the ground by the safety operators. This neutralization is effective in near field phase.

There are two main types of mitigation measures:

• Preventive measures relying mainly on the launcher reliability;
• Corrective measures relying mainly on launcher neutralization.

All the mitigation measures identified in the effect synthesis sheets, cf. Table 3, are gathered in appendix of the hazard study. Hereafter some generic mitigation measures:

• Mitigation measures designed in development phase, as:
  ◦ Definition of meteorological criteria for launch;
  ◦ Design of neutralization chains to be remotely controlled by the safety operators;
  ◦ Conception of dedicated tools and models, to be used in exploitation for the safety submissions files;
  ◦ Definition and implementation of on-board automatic neutralization systems
  ◦ Definition of test logic implemented in the flight software, in case of failure detection
  ◦ Design of the passivation system;
  ◦ …

• Mitigation measures to be applied in exploitation by the launch system operator:
  ◦ Respect of meteorological criteria for launch;
  ◦ Maintenance of the system in qualified domain
  ◦ Measures relative to mission analysis and inputs required in the safety submission (trajectory, flight corridor, fallback areas, tuning of predictive criteria, fragmentation model, casualty risk computation, injection accuracy, …)
  ◦ Tuning of the flight software using mission analysis results
  ◦ …

For each mitigation measure, the reference of the associated effect synthesis sheet is kept to ease the follow-on and traceability.

5. DIFFERENT TYPES OF HAZARD STUDIES

5.1 Delta hazard study

A typical hazard study covers a generic mission. For Ariane 5 program, the following dedicated hazard studies have been performed to cover the following generic missions:

• A5/ECA GTO dual launch;
• A5/ES ATV;
• A5/ES Galileo.

For these missions, the hazard study is based upon generic trajectories characterized by a qualified domain of key parameters, as launch azimuth, final orbit, which fix the safety key events of the flight sequence. For each flight, the launch system operator provides safety submissions to check that the specific flight is still inside the generic domain and does not question the hazard study.

Some particular missions are outside the generic domain, due to system or hardware evolutions, leading to the need of additional development to demonstrate their flight-worthiness. This leads to re-defining a specific flight sequence, trajectory, fallback areas, visibility from ground station, logic of deorbit, etc., and therefore it is necessary to carry out a specific hazard study.

Such hazard study, emitted for few launches or even for one launch only, can be briefer than a generic hazard study, and can focus only on the difference between the specific mission and the generic ones. The main benefit of this approach is to highlight the safety and regulatory impacts and to manage them by particular mitigation measures. It allows also to reduce the amount of work necessary to conduct the analysis, which is performed by delta comparison with an existing generic hazard study.

The used methodology for these delta hazard studies follows the different steps:

• Identification of the generic mission which is closest to the specific mission, in terms of trajectories or hardware.
• Description of the particularities of the new mission in terms of hardware, flight sequence and trajectories.
• For each effect identified in the synthesis table (cf. Table 2), assessment if the new mission has an impact or not on it.
• In case of impact, description of the demonstration provided by the project and identification of the specific mitigation measures that have to be done in development or in exploitation.
A new synthesis table is therefore established by the addition of 2 columns to the initial synthesis table (cf. Table 2), corresponding to the 2 latter bullets of the proposed methodology.

For Ariane 5, this methodology has been applied for the following specific missions, with a delta hazard study compared to the A5 / ECA GTO dual launch.

- A5/ECA GTO single launch
- A5/ECA GTO Demoflight (Commercial mission with additional experimental maneuvers performed after the payloads jettisoning for microgravity characterizations)

5.2 Preliminary hazard study

As a benefit of its simplification, the hazard study methodology is easier to be implemented. Consequently it appears that this tool can be used very early in a development project. The systematic approach aiming at the exhaustiveness of the identification of the potential effects on humans and environment allows to identify all the technical analyses to be done in the scope of the demonstration of the compliance to the technical requirement of chapter 3 of the TR. This approach is now implemented for all the Ariane future missions and complementary developments. The following preliminary hazard studies have been performed for the following missions:

- A5/ECA Upper Part Adaptation;
- A5/ECA mission with Bepi Colombo (mission toward Jupiter);
- A5/ECA mission with the James Webb Space Telescope;

As these missions used the A5/ECA version, the format of the hazard study is similar to the format described in §5.1 for the delta Hazard analysis.

6. SYNTHESIS

Since the French Space Operation Act and the associated regulations came into force in 2010, the methodology used to establish the launch system hazard studies has been improved in order:

- to ease its readability;
- to facilitate its drafting.

This improvement has been implemented without loss of exhaustiveness and with a better overview of the logic of risk mitigation, demonstration of the compliance to the regulatory requirements, through the synthetic sheets produced for each potential effect on humans or environment.

As a result, the diffusion has been enlarged and the hazard study is no more only a regulatory document, but is also more widely used as a project tool which summarizes the risk management of the safety feared events. In this way the template of the hazard study is flexible and can be adapted to different types of situations, from a complete hazard study covering a generic mission domain, to a delta hazard study covering an evolution of the launch system by an assessment of the impact of each evolution all along the flight sequence. Preliminary hazard study, performed before the start of development, also allows to anticipate and optimize the mitigation measures, and to have a better follow-up of their implementation.

7. REFERENCES

A0. Loi N° 2008-518 du 3 juin 2008 relative aux opérations spatiales


A3. Arrêté relatif à la Réglementation Technique en application de la Loi n° 2008-518 du 3 juin 2008 relative aux opérations spatiales - 31/03/2011

A4. Arrêté portant Réglementation de l’Exploitation des Installations du Centre Spatial Guyanais - 09/12/2010

A5. F. Meyer Lassalle, G. de Blanchard, C. Aussilhou (2011) Launch system hazard study, methodology and application with 3 European launchers, IAASS, Montreal (2011)
Progress in space safety lies in the acceptance of safety design and engineering as an integral part of the design and implementation process for new space systems. Safety must be seen as the principle design driver of utmost importance from the outset of the design process, which is only achieved through a culture change that moves all stakeholders toward front-end loaded safety concepts. Superb quality information for engineers, programme managers, suppliers and aerospace technologists.

Space Safety Regulations and Standards provides the practical how-to guidance and knowledge base needed to facilitate safe and effective operations safety in line with current regulations. With information on space operations safety design currently disparate and difficult to find in one place, this unique reference brings together essential material on: safety design practices, advanced analysis methods, and implementation procedures.
GLOBAL SPACE EXPLORATION CONFERENCE (GLEX 2017)

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The GLEX 2017 programme is designed to bring together leaders and decision-makers within the science and human exploration community – engineers, scientists, entrepreneurs, educators, agency representatives and policy makers. It will provide a forum to discuss recent results, current challenges and innovative solutions and it will contain several opportunities to learn about how space exploration investments provide benefits as well as discuss how those benefits can be increased through thoughtful planning and cooperation.

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