

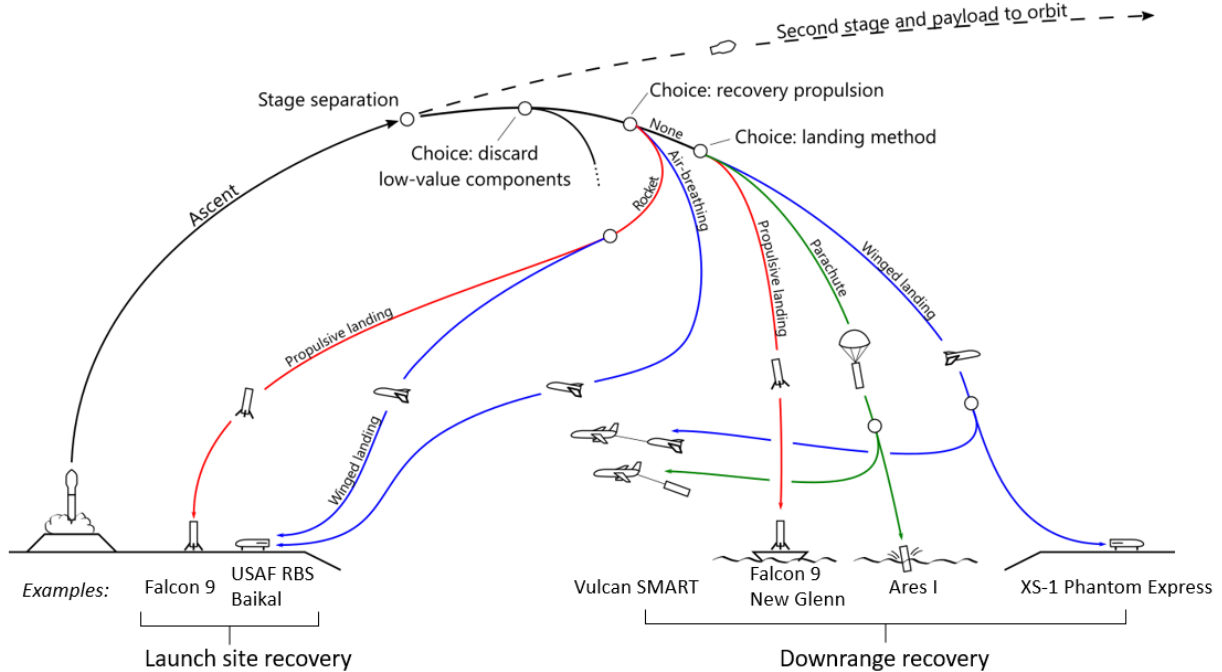
## I. Classification of first stage reuse strategies

Although only two vehicles with recoverable stages have been operated, a wide variety of first stage recovery strategies have been proposed. This section develops a systematic classification of recovery strategies.

First stage recovery strategies can be classified by four high-level choices:

- 1) *Recovery location* - The stage may return itself for recovery at the launch site, or may be recovered downrange. Launch site recovery would occur on land. Downrange recovery could occur on a ship, directly in the ocean, on land, or midair with recovered components being caught by an aircraft [1, 2].
- 2) *Recovery propulsion method* - The stage may propel itself to the recovery location by firing its rocket engines or by using additional air-breathing engines. Alternatively, the stage may not use propulsion during recovery, and instead glide or fall to the recovery location.
- 3) *Landing method* - The stage may use rocket engines to land vertically (propulsive), land horizontally like an airplane (winged), or land under parachutes.
- 4) *Portion of 1<sup>st</sup> stage recovered* - Some strategies recover the entire first stage, while others propose to only recover a portion containing the higher-value components (e.g. main engines [1]).

In this paper, a "reuse strategy" will denote a combination of answers to these four choices. There are 90 possible choice combinations, of which 36 seem vaguely feasible. Of these, 11 distinct strategies have been operated or proposed (Table 1). Figure 1 illustrates the concept of operations for some of these strategies.



**Fig. 1 Many different strategies can be employed to recover and reuse the 1<sup>st</sup> stage of a launch vehicle.**

The following sections will estimate the performance and cost per flight of several of the above reuse strategies.

## References

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**Table 1 Examples of first stage reuse strategies.**

Vehicle	Status	Recovery location	Recovery propulsion method	Landing method	Portion of 1 <sup>st</sup> stage recovered
Falcon 9 [3]	Operational	Launch site or downrange	Rocket	Propulsive	Full
Space Shuttle*	Retired	Downrange	None	Parachute	Full
New Glenn [4]	Proposed	Downrange	Rocket	Propulsive	Full
XS-1 Phantom Express [5, 6]	Proposed	Launch site or downrange	None	Winged	Full
SMART (Vulcan) [1]	Proposed	Downrange (midair)	None	Parachute	Partial
Adeline (Ariane 6)	Canceled [7]	Launch site	Air-breathing	Winged	Partial
Ares I [8]	Canceled	Downrange	None	Parachute	Full
Reusable Booster System (RBS) [9]	Canceled	Launch site	Rocket	Winged	Full
Kistler K-1 [10]	Canceled	Launch site	Rocket	parachute	Full
NASA Liquid Fly-Back Booster (LFBB)* [11]	Canceled	Launch site	Air-breathing	Winged	Full
DRL Liquid Fly-Back Booster (LFBB)* [12]	Canceled	Launch site	Air-breathing	Winged	Full
Baikal [10]	Canceled?	Launch site	Air-breathing	Winged	Full

\* denotes boosters used in parallel staging.

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- [12] Sippel, M., International Astronautical Congress (IAF), American Institute of Aeronautics and Astronautics, 2003, Chaps. Long-Term / Strategic Scenario for Reusable Booster Stages. doi:10.2514/6.IAC-03-V.4.02, URL <https://doi.org/10.2514/6.IAC-03-V.4.02>, 0.