TYPICAL TECHNOLOGY OF MECHANICS ON GEN-III PASSIVE NPPs AND GEN-IV ADVANCED SUPERCRITICAL LIGHT WATER REACTORS

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Background（1/4）

- **American Utility Requirements Document (URD) for advanced light water reactors defines the technical bases for innovated and standardized future LWR design. Those are:**

✓ Simplification

✓ Design margin

✓ Human factors

✓ ALWR safety

✓ ALWR design basis versus safety margin

✓ Regulatory stabilization

✓ Plant standardization

✓ Use of proven technology

✓ Maintainability

✓ Quality assurance

✓ ALWR economics

✓ ALWR sabotage protection

✓ ALWR good neighborhood, etc.

Background（2/4）

- New Gen NPPs or called as Gen-III passive advanced plant, compared with traditional PWRs, the number of valves, pumps, pipelines, cables, dampers reduced 50%, 35%, 80%, 70%, and 80%, respectively, the volume of seismic structures reduced 45%, while nuclear steam supply system remained utilizing proven technology.

Background（3/4）

- Thus, some new issues of mechanics are brought forward, such as:

✓ load-carrying capability evaluation for steel containment

✓ in-vessel retention of molten core debris (IVR)

✓ seismic design without considering OBE

✓ thermo-hydraulic issues concerning coupling between two-phase fluid and solid, etc

Background（4/4）

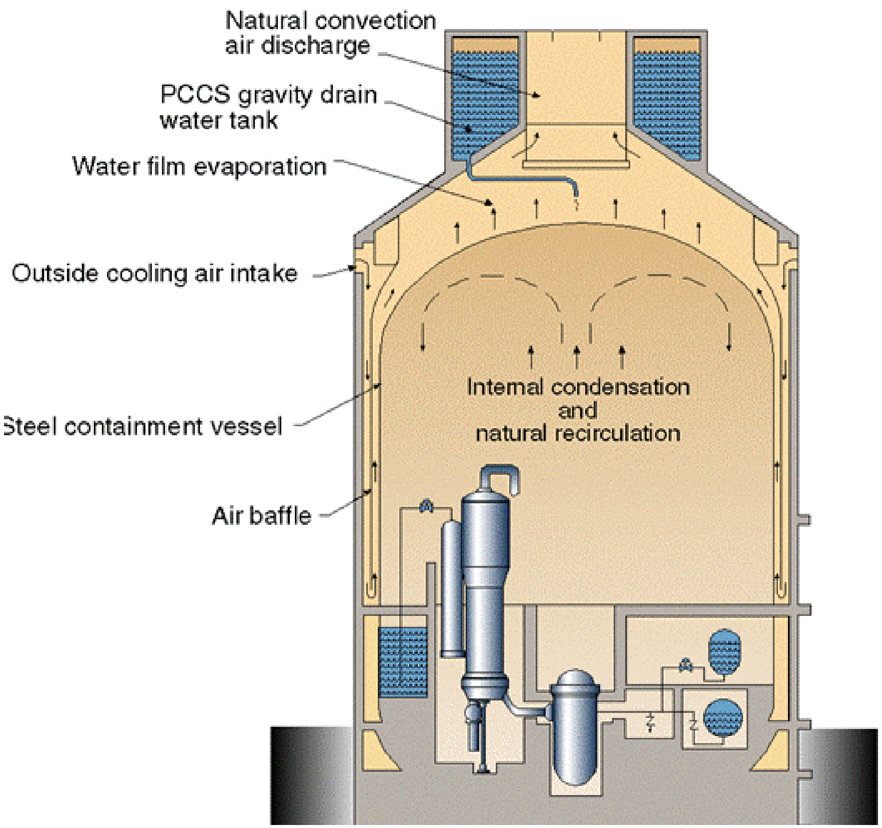
- As to the so-called Gen-Ⅳ reactor, which focuses on renovation of reactor itself, an example is the Supercritical Water-Cooled Reactor (SCWR).
- besides the in-core thermo-hydraulic and fuel design problems, mechanical and material problems (e.g. pressure fluctuation with shock wave shape caused by the supercritical fluid in the core, creep of materials working under high temperature, etc.) are also main obstacles that prevent the concept from coming true.

Main Mechanics for Design of Gen-III Passive Advanced NPP（1/11）-Main Features of Design

- The main features of Gen-III passive advanced NPPs are simplification and passive design concepts, which makes the plants safe and economic.

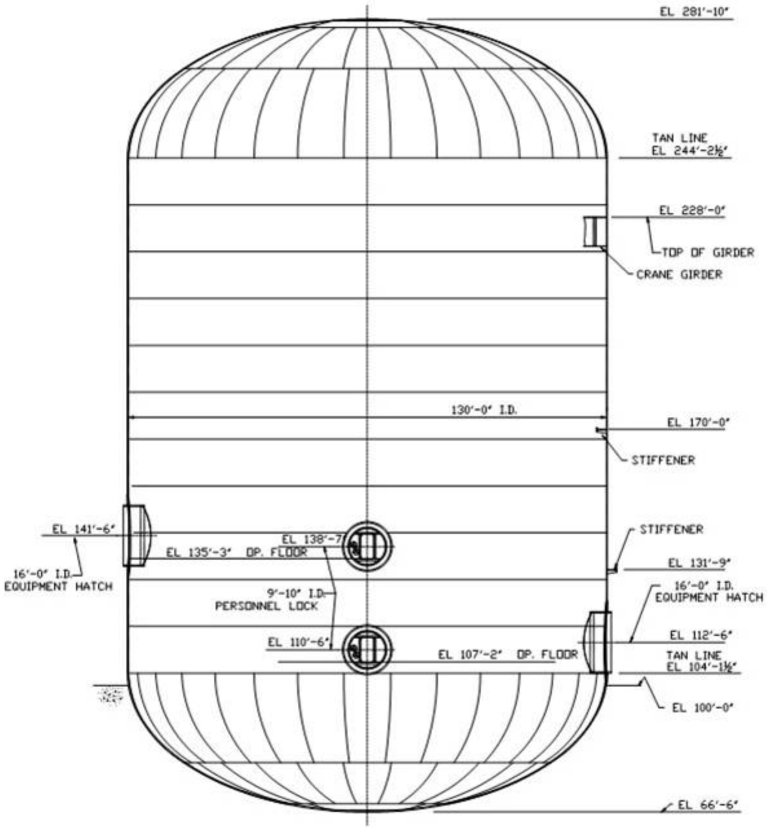
Main Mechanics for Design of Gen-III Passive Advanced NPP（2/11）-Pressure Load-Carrying

- a typical example is the containment cooling system of AP1000, see right Fig..
- it has a double-layered containment structure: the inner layer is steel containment and the outer, concrete structure.



Main Mechanics for Design of Gen-III Passive Advanced NPP（3/11）- Pressure Load-Carrying

- Steel containment vessel is assembled with cylindrical shells and two semi-ellipsoidal heads.
- When LOCA or severe accident happens and steam pressure in the containment increases, it is necessary that the steel containment should be able to bear the pressure load and that steam pressure should be confined within its allowable limit.

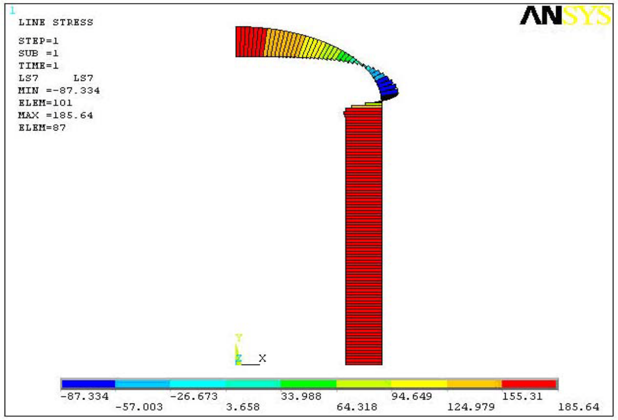


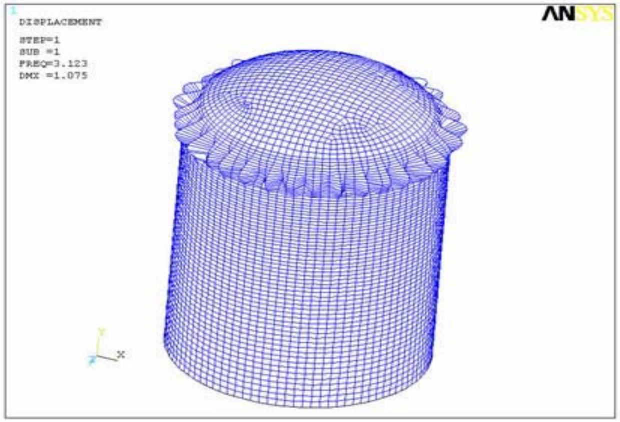
Main Mechanics for Design of Gen-III Passive Advanced NPP（4/11）- Pressure Load-Carrying

- **Two aspects should be considered so as to obtain the ultimate pressure load-carrying capability of steel containment:**
  - ✓ **one is to ensure that the stress or strain be controlled within its limits.**
  - ✓ **the other is to ensure that the buckling load and displacements be limited within its allowable values.**

Main Mechanics for Design of Gen-III Passive Advanced NPP（5/11）- Pressure Load-Carrying

- **The right Figs. show that compression stress will occur in some local regions of the steel containment when it is loaded by internal pressure, which causes local buckling. So coupling analysis taking account of both plasticity and buckling effects is implemented to obtain the final pressure load-carrying capability of the structure. In the design of Gen-Ⅲ passive AP1000, the load-carrying capability is evaluated with different analytical methods, which shows the bearing capabilities obtained from different methods accord with each other by and large.**





Main Mechanics for Design of Gen-III Passive Advanced NPP（6/11）- In-Vessel Retention

- When core meltdown accident happens, the molten core debris may be designed retaining in reactor vessel while the bottom of reactor vessel shouldn’t get melted, which reduces the possibility that radioactivity is let out so that accident sequence is mitigated.

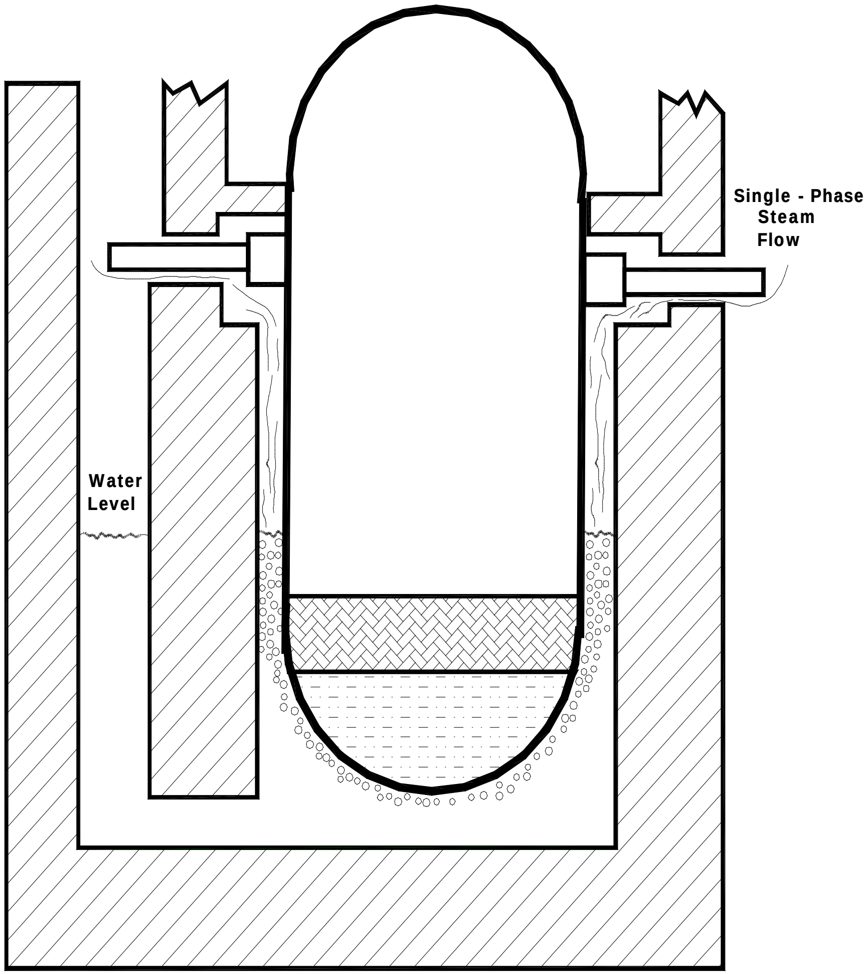
Main Mechanics for Design of Gen-III Passive Advanced NPP（7/11）- In-Vessel Retention

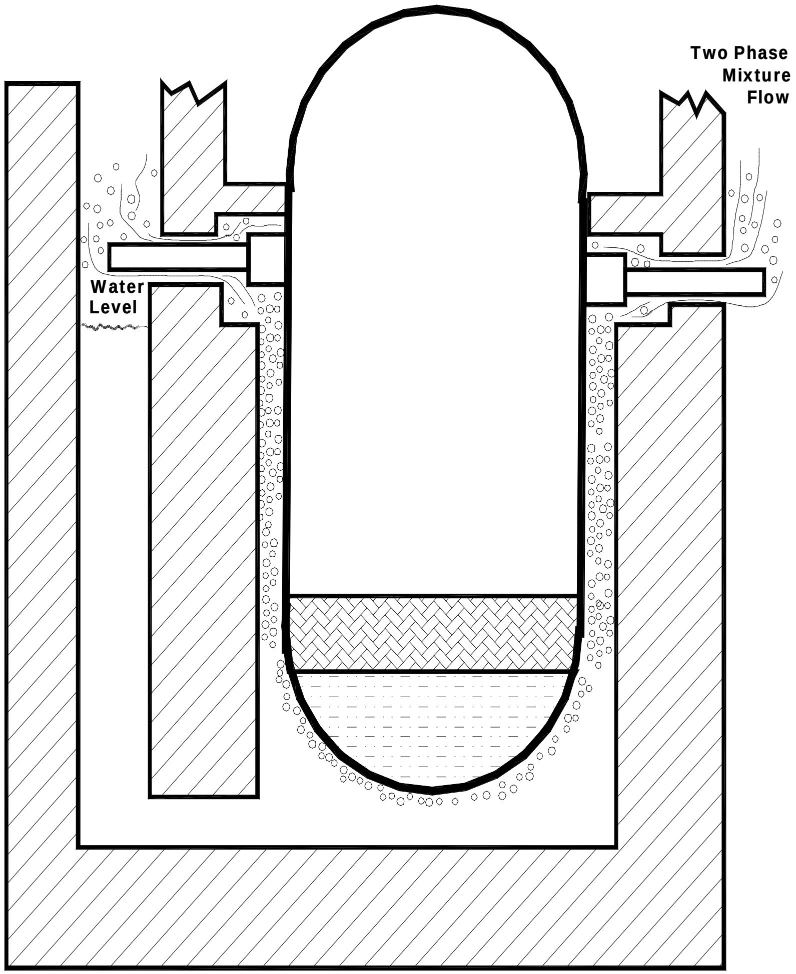
- the following two mechanical issues should be taken into account:

✓ Cooling and releasing issue of the core cavity water—it is a thermo-hydraulic problem concerning coupling between two-phase fluid and solid, that is, the problem is about heat transfer and heat conduction between two-phase fluid injected and RPV solid.

✓ Creep failure of RPV at high temperature— at high temperature, material durability limit will decrease as time passes and creep strain will increase. Material nonlinearity at high temperature and creep failure analysis are also difficulty of this item.

Main Mechanics for Design of Gen-III Passive Advanced NPP（8/11）- In-Vessel Retention





Main Mechanics for Design of Gen-III Passive Advanced NPP（9/11）- No OBE Seismic Design

- One of the standardized designs of advanced PWR is seismic design standardization. To simplify seismic design, URD uses no OBE seismic design method, which reduces the total investment of seismic design from original 8~10% to below 5%.
- The seismic design contents basically contain seismic classification in nuclear power plant, seismic requirements for OBE abrogation, seismic margin evaluation and seismic risk evaluation, etc.

Main Mechanics for Design of Gen-III Passive Advanced NPP（10/11）- Two Phase Issue

- The replacement and supplement of passive safety systems ingeniously take advantage of the simple physical law of nature, “gravity”, to design cooling in natural circulation form, which greatly reduces quantity of facility and components and thus failure possibility of system and equipment is also decreased.

Main Mechanics for Design of Gen-III Passive Advanced NPP（11/11）- Two Phase Issue

- **In order to ensure that the passive system can maintain its natural circulation function, strict analyses and tests shall be implemented to solve thermo-hydraulic issues that concern coupling between two-phase fluid and solid. The steel containment is a typical example. The fluids are two-phased with gas and liquid states, and they are coupled with the containment shell to transfer heat, which makes it rather difficult to be analyzed.**
- **Besides, the thermo-hydraulic fluid-structure coupling in IVR is more difficult, so both mechanical and thermo-hydraulic engineers should put more emphasis on it.**

Main Mechanics for Design of Gen-Ⅳ SCWR (1/8）- Main Features of Design

- In May 2000, the Generation IV International Forum (GIF) selected 6 most promising reactor types as Gen-IV advanced reactor systems. Here only take “Supercritical Water-cooled Reactor” (SCWR) as an example, whose design principle is shown in Fig..

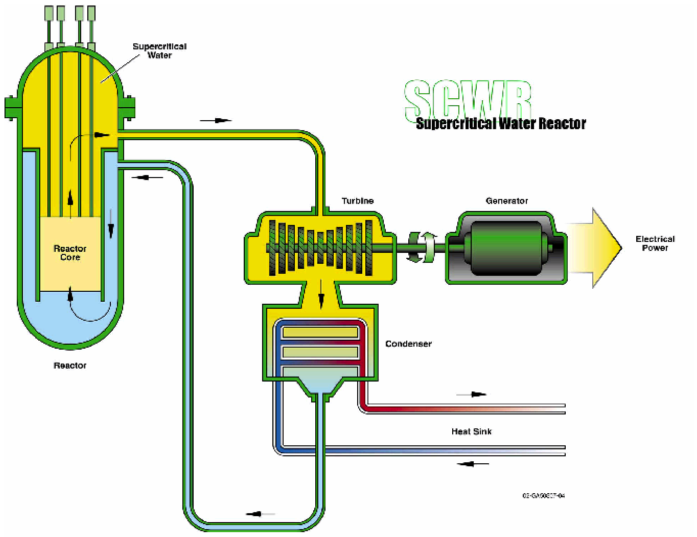


Fig. 5 Design Principles of SCWR

Main Mechanics for Design of Gen-Ⅳ SCWR (2/8）- Main Features of Design

- The pressure vessel and core construction form of SCWR are similar to those of PWR, yet the coolant of SCWR works above the thermodynamic critical point of water (374℃，22.1MPa) and this kind of “cooling water” has dual nature of liquid and gas, which makes the heat conduction efficiency better than that of ordinary light water. Compared with current light water reactor, the heat efficiency of SCWR is enhanced by one third. The main reference values of SCWR parameters are listed in next Table.

Main Mechanics for Design of Gen-Ⅳ SCWR (3/8） - Main Features of Design

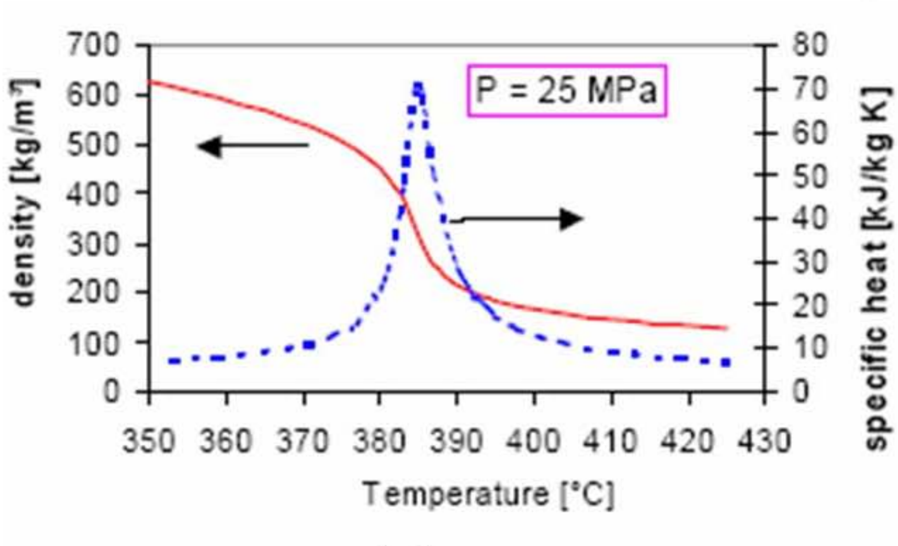
Parameter	Unit	Value
Power	MWe	1700
Coolant pressure	MPa	25
Coolant inlet temperature	℃	280
Coolant outlet temperature	℃	510
Net efficiency	%	44
Fuel		UO_2
Burnup	GWP/MTHM	45
Damage	dpa	10-30

Table Reference Value of SCWR Main Parameter

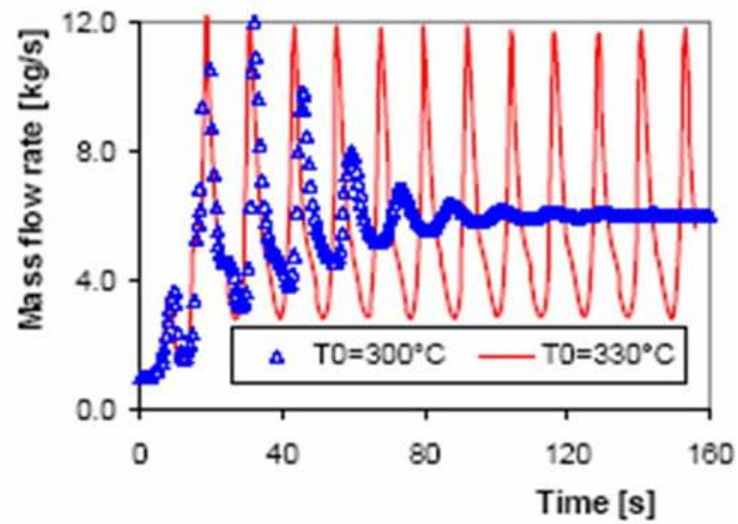
Main Mechanics for Design of Gen-Ⅳ SCWR (4/8）- Mechanical Difficulties for Further Researches

- The core inlet and outlet temperatures are 280° /510℃, respectively, so the temperature increase of coolant inside the core (4~5 meters in height) is 230℃, which means the temperature increases rapidly. And the coolant inside the core has to get through the critical point of 374℃, under which temperature physical properties of “water”, such as its density, specific heat capacity, etc. will change suddenly (See Fig.).

Main Mechanics for Design of Gen-Ⅳ SCWR (5/8） - Mechanical Difficulties for Further Researches



（a）



（b）

Main Mechanics for Design of Gen-Ⅳ SCWR (6/8）- Mechanical Difficulties for Further Researches

- **Fluid dynamic response induced by the sudden change of thermo-hydraulic parameters near critical point will cause some severe influences listed as follow:**

① "Shock Wave" effect will occur near critical point, which means parameters such as pressure, density, etc., will change suddenly.

② Mass flow, pressure will fluctuate (See Fig.).

③ Structure "flutter" may be induced, which is a hundred times as severe as, if not more severe than, flow-induced vibration in current PWRs.

Main Mechanics for Design of Gen-Ⅳ SCWR (7/8）- Mechanical Difficulties for Further Researches

- The design temperatures of Gen-II or Gen-III reactor vessel are both below creep temperature of the material and influence of creep is not required to consider. However, the temperature and pressure of SCWR are even higher, so it is necessary to take account of the cumulative coupling damage effect associated with high-temperature creep and fatigue upon component life for coolant loop. For material of RPV core, further consideration should be given to acceleration effect of creep induced by irradiation.

Main Mechanics for Design of Gen-Ⅳ SCWR (8/8）- Mechanical Difficulties for Further Researches

- Since no steam generators are designed in SCWR, supercritical water directly enters the steam turbine and does work. Hence the pressure boundary of steam turbine belongs to nuclear Class 1, which makes dynamic sealing of its rotor bearing a technical difficulty of operation and maintenance.

Conclusions（1/2）

- From aforementioned discussions on mechanical issues and technical difficulties associated with Gen-III passive NPPs and Gen-IV advanced SCWR, we may clearly make out that the differences between mechanics of Gen-III or Gen-IV NPPs and those of current NPPs are as follow:

(1) Thermo-hydraulic dynamics and structural dynamics coupling issues become dominant.

(2) Creep at high temperature and fatigue coupling damage accumulation should be given attention to.

Conclusions（2/2）

- To solve these issues, we should utilize principles and methods of modern applied mechanics, i.e. traditional solid and structure mechanics, fluid mechanics, thermodynamics, material science, computer simulation technology, etc. and cross-disciplines of these subjects.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