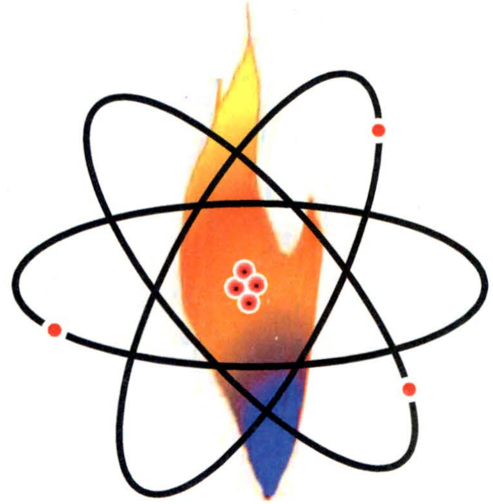
HYBRID-NUCLEAR ENERGY



Hybrid Power Technologies LLC

Concept

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PREFACE

The objective of this text is to introduce a new approach to power generation.

The concept bases for this innovative technology are examined, including discussions of major elements required for success in a competitive power industry.

This illustrated text is aimed at the general public, students, energy professionals, and government regulators. Important considerations are simply introduced, evaluated, and summary conclusions provided.

Comparisons are made with other forms of electrical generation. These contrasts are generally on a relative basis, as opposed to absolute standards. The comparisons, while helpful, are not intended for drawing universal conclusions for all situations.

In summary, the text provides insights into a unique hybrid-nuclear solution for sustainably and affordably meeting the world's energy needs using environmentally sound methods involving the marriage of nuclear and fossil fuels.

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CONTENTS

TERMINOLOGY

Ag Silver
Ar Argon
CH_2 Methylene
CH_3 Methyl Group
CH_4 Methane
C_2H_2 Acetylene
C_3H_6 Cyclopropane
CO_2 Carbon Dioxide
H_2 Hydrogen
He Helium
Hg Mercury
NO_x Nitrogen Oxides
N_2 Nitrogen
Pu Plutonium
O_2 Oxygen
$SiCl_3$ Methyltrichlorosilane
SO_2 Sulfur Dioxide
Th Thorium
U Uranium
UO_2 Uranium Oxide
UF_6 Uranium Hexafluoride
U_3O_8 Triuranium Oxide (yellow cake)

ή Efficiency
µ micro

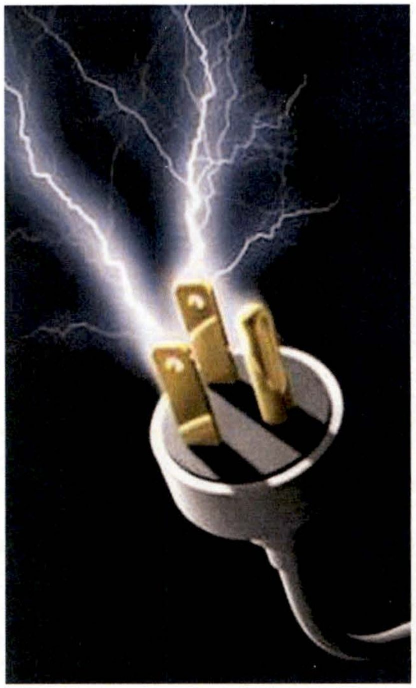
AC Alternating Current
ASME American Society of Mechanical Engineers
CAES Compressed Air Energy Storage
CFR Code of Federal Regulations
CTLG Coal-to-Liquids or Gases
DC Direct Current
EPA Environmental Protection Agency
EPC Engineer, Procure Construct
EPRI Electric Power Research Institute
FPHE Formed Plate Heat Exchanger
GDC General Design Criteria
HTGR High-temperature Gas Reactor
IGCC Integrated Gasification Combined-cycle
IPP Independent Power Producer
ISCC Integrated Solar Combined-cycle
ISO International Organization for Standardization
NGCC Natural Gas Combined-cycle
NRC Nuclear Regulatory Commission
REM Roentgen Equivalent Man
SCR Selective Catalytic Reduction
SMR Small Modular Reactor

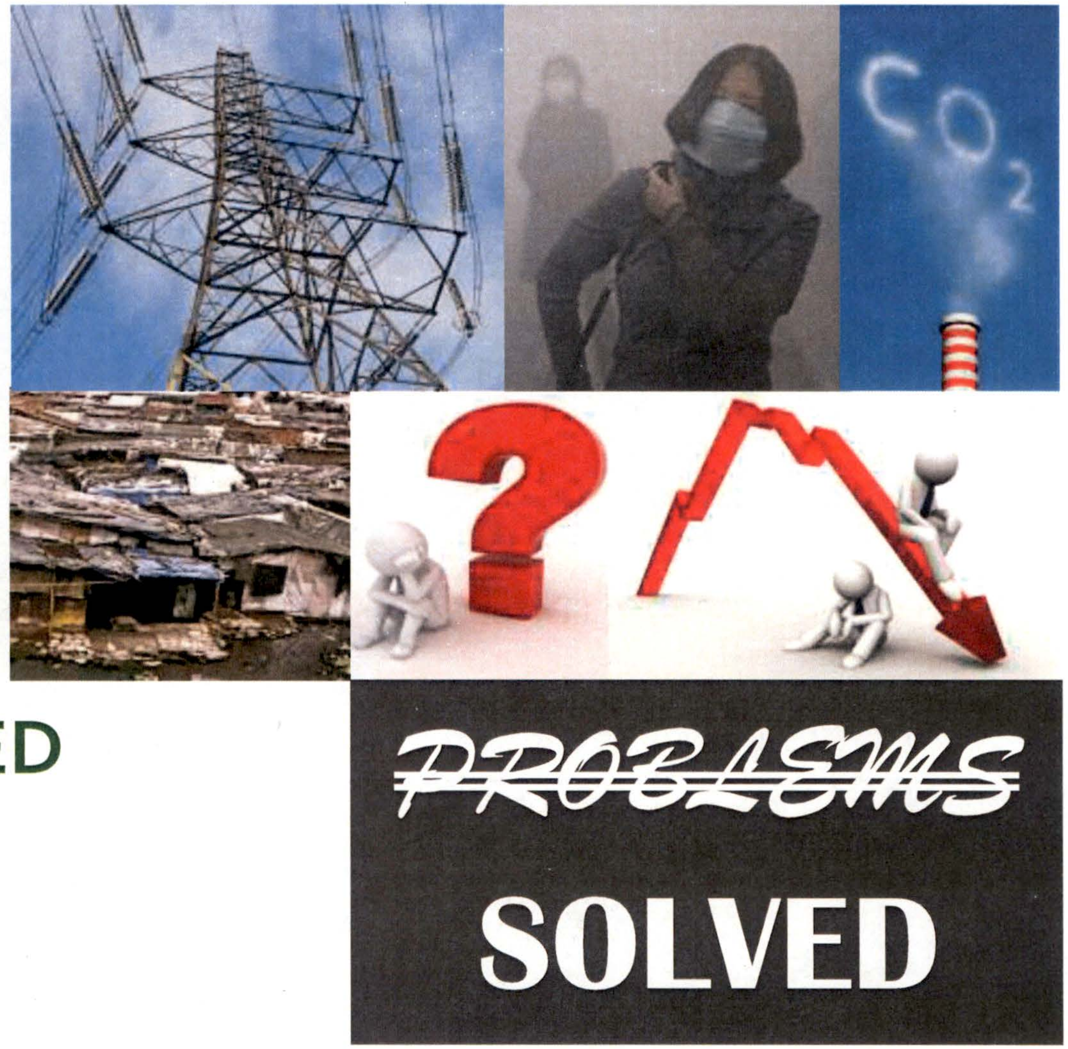
BTU British Thermal Unit
cm centimeter
Ft foot, in inch
g gram
HHV Higher Heating Value
KV Kilovolt (1000 Volts)
KW Kilowatt (1000 Watts)
L Diffusion Length
lbm pound
LHV Lower Heating Value
m meter
MGD million gallons/day
mm millimeter
MMBTU million BTU's
MW megawatt
- **MW(e)** electric
- **MW(t)** thermal
- **MWh** hour

ppm part per million
Pressure
- **BAR** 14.7 psig
- **HP** High
- **IP** Intermediate
- **LP** Low
- **psig** lbm per inch^2 gage

Temperature
- **°C** Celsius
- **°F** Fahrenheit

INTRODUCTION: *Energy*

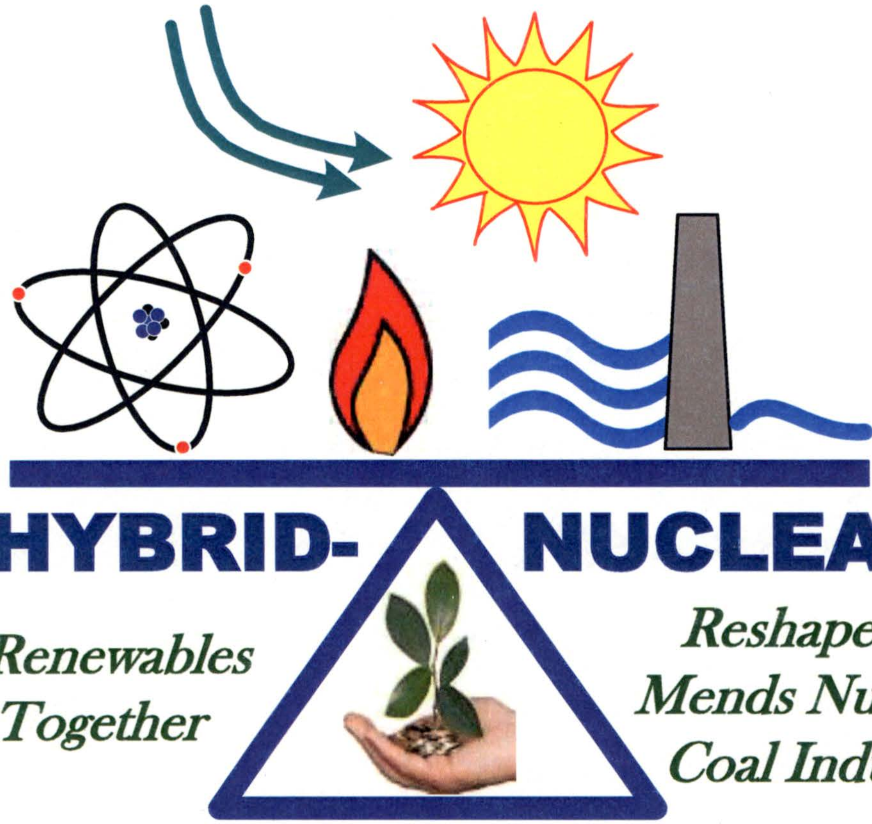




- CRITICAL NEED
  - ✓ **Affordable**
  - ✓ **Plentiful**
  - ✓ **Clean**

INTRODUCTION: *Energy*

/21st Century *Solution*



Balanced Use of All Resources

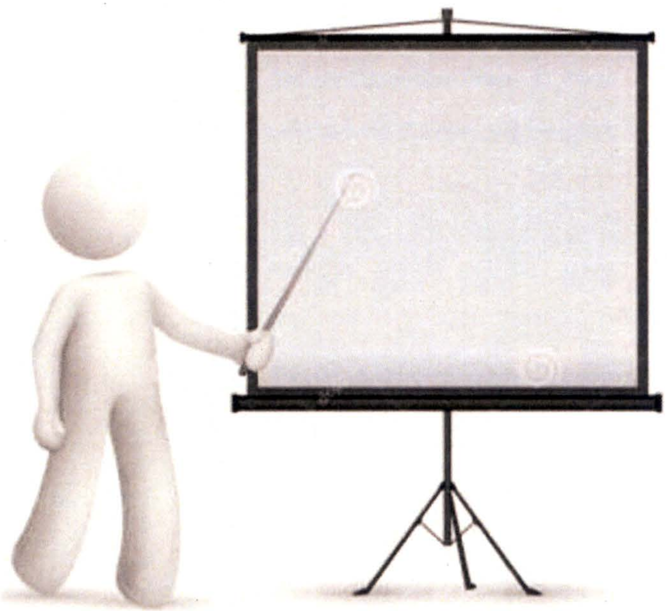
HYBRID-NUCLEAR

Nuclear, Fossil & Renewables Safely Working Together

Reshapes and Mends Nuclear & Coal Industries

Profitable
Reasonably Priced
Environmentally Friendly

OVERVIEW



Historical Perspective

The development of technology generally occurs as the result of incremental evolutionary steps that collectively produce more cost effective products. However, occasionally innovations arise that are both unexpected and transformational.

OVERVIEW: *Competition*

- ***MUST BE <u>BETTER</u> than EXISTING PRODUCTS <u>To WIN</u> in MARETPLACE***

CONCEPT

OVERVIEW: *Hybrid Vision*

❖ **CLEANLY, AFFORDABLY & SAFELY HELP FUTURE GENERATIONS USING *ALL* ENERGY RESOURCES**

(natural gas, nuclear, coal, renewable)

No Other Technology Can Match Hybrid

CONCEPT

OVERVIEW: *Hybrid Mission*

- SIGNIFICANTLY IMPROVE GAS TURBINE USING MORE PRACTICAL, SAFER NUCLEAR GAS REACTOR

CONCEPT

OVERVIEW: *Hybrid Key Features*

- **NEW & UNIQUE … but**
  Adapts Current Technologies … Practical
- **COMPETITIVE**
  US Owned … Numerous Applications
- **ENVIRONMENTALLY FRIENDLY**
  Massive Waste Reductions … Low Impacts
- **SMALL REACTOR**
  Fail-safe … Readily Licensed.

CONCEPT

BACKGROUND

Historical Perspective

Power production using heat has been an engineering challenge since the 19th century. Coal fired boilers, designed to generate steam subsequently used to rotate a turbine/generator, have been a mainstay for well over a hundred years. Through the years, modest efficiency improvements to reduce production costs have been made by increasing steam pressures and temperatures.

With the advent of the gas turbine in the late 1930'3, the electrical production potential of these machines was quickly recognized. However, the early machines were very inefficient and improvement efforts involved both "open" systems (atmospheric air pressurized, heated, routed through turbine, and discharged back to the environment) as well as "closed" systems (air internally recirculated and externally heated) – **Ref. 22***. Ultimately, the "open" system seen in today's gas turbines won out. Significant efficiency improvements (associated with higher firing temperatures and pressures) have steadily occurred.*

The power production capability of nuclear energy was also quickly recognized with electricity first generated in the early 1950's – **Ref. 24***. Several reactor types emerged from the development process. Ultimately the water cooled reactor used to produce steam emerged as today's dominate power production facility. Efficiency improvements have been largely stagnant owing to limitations associated with using water in a reactor - the fuel can overheat and melt. Gas reactors have efficiency advantages because the machines run hotter than water reactors and the fuel is not prone to melting. However, such facilities are uncommon.*

BACKGROUND: *Conventional*

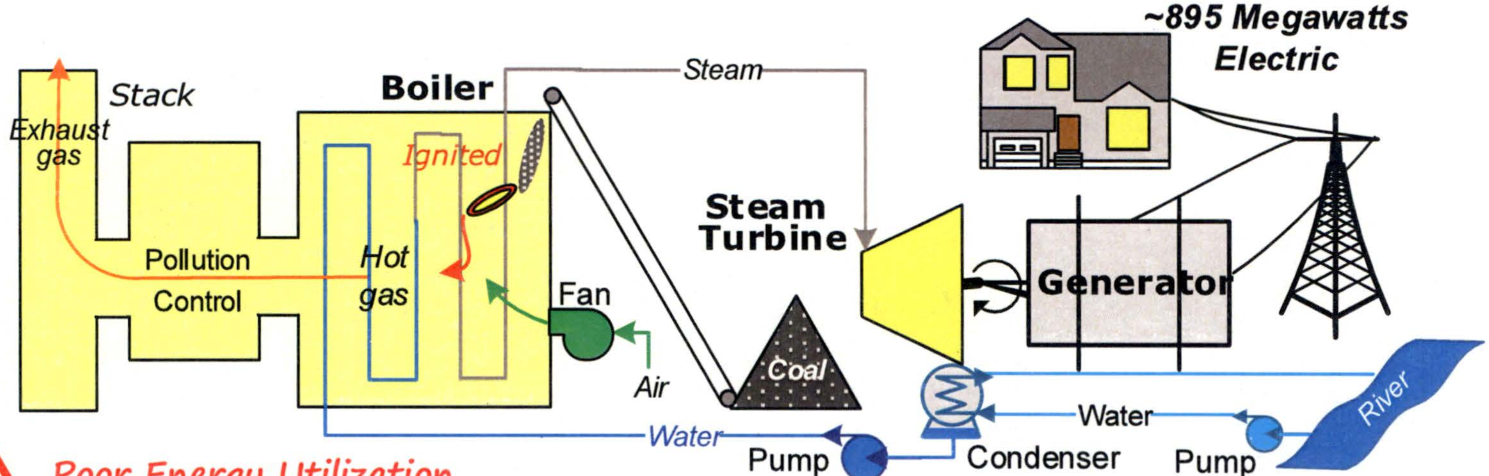
/Coal Plant

➢PULVERIZED COAL[1]

- Crushed Coal & Air Ignited in Boiler
- Hot Gas Boils Water
- Steam Rotates Turbine/Generator
- Massive Structure – Boiler & Pollution Control Equipment

Coal

About 646,000 homes,
~895 Megawatts Electric



Poor Energy Utilization
~36% Efficient

Worlds 1st
Commercial Coal Power Station
1882 USA

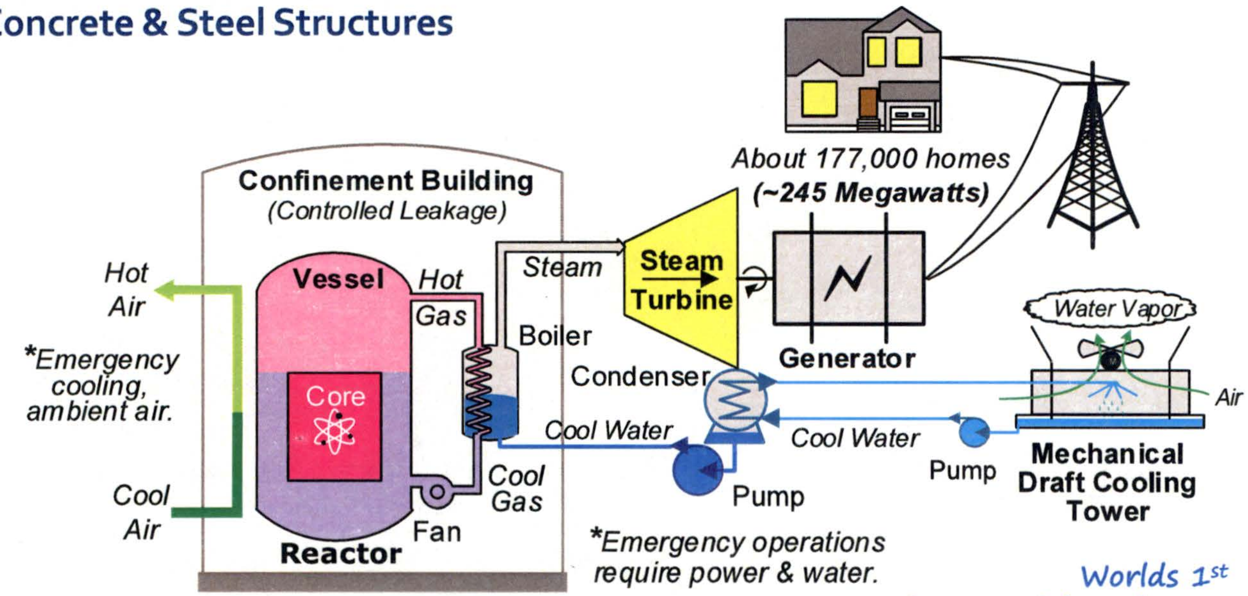
Note: *(1) Supercritical Pulverized Coal (SCPC). Steam at high pressures & temperatures, typically +2500 psig/ 170 BAR & +1000°F/535°C.*

CONCEPT

BACKGROUND: *Conventional*
/Nuclear Plant - *Gas*

➢GRAPHITE REACTOR[1]
Gas Reactor

- CO_2 or Helium Cooled
- Graphite Moderated (Neutrons slowed down)
- Hot Gas Boils Water & Steam Rotates Turbine/Generator
- Large Concrete & Steel Structures



More Efficient than Water Reactors
~40% versus ~34%

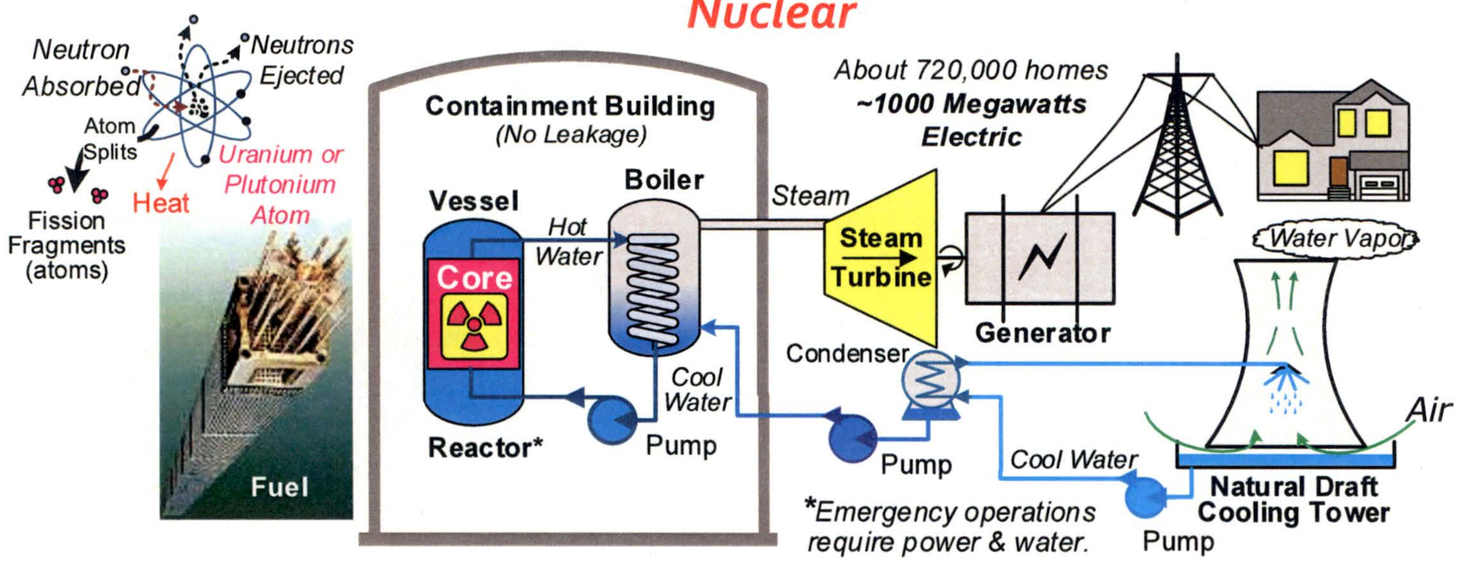
Worlds 1st
Commercial Nuclear Power Station
Gas Reactor
1956 Great Britain

Note: *(1)* A number of *gas reactors have been deployed, but all have employed steam generators for power production owing to the technical immaturity of directly using a gas turbine - see* **Technical** *Chapter, End-note* ***G***.
(2) *Advanced Gas Reactor (Great Britain) CO_2 pressure & temperature: +1665 psig/40 BAR & +1190°F/645°C. Steam pressure & temperature +2400 psig/165 BAR & +1000°F/540°C. Output ~660 MW(e), Reactor ~1500 MW(t)* **Ref. 38.**

CONCEPT

BACKGROUND: *Conventional*
/Nuclear Plant – *Water*

➢METAL TUBE REACTOR
- Water Cooled & Moderated *(Neutrons slowed-down)*
- Core Heats Water to Create Steam
- Steam Rotates Turbine/Generator[1]
- Large Concrete & Steel Structures



⚠ *Poor Energy Utilization*
~34% Efficient

Worlds 1st
Commercial Pressurized Water Reactor
Nuclear Power Station
1957 USA

CONCEPT

Note: *(1) Typical steam pressure & temperature +1000 psig/65 Bar & +570°F/300°C.*

 Rev. A

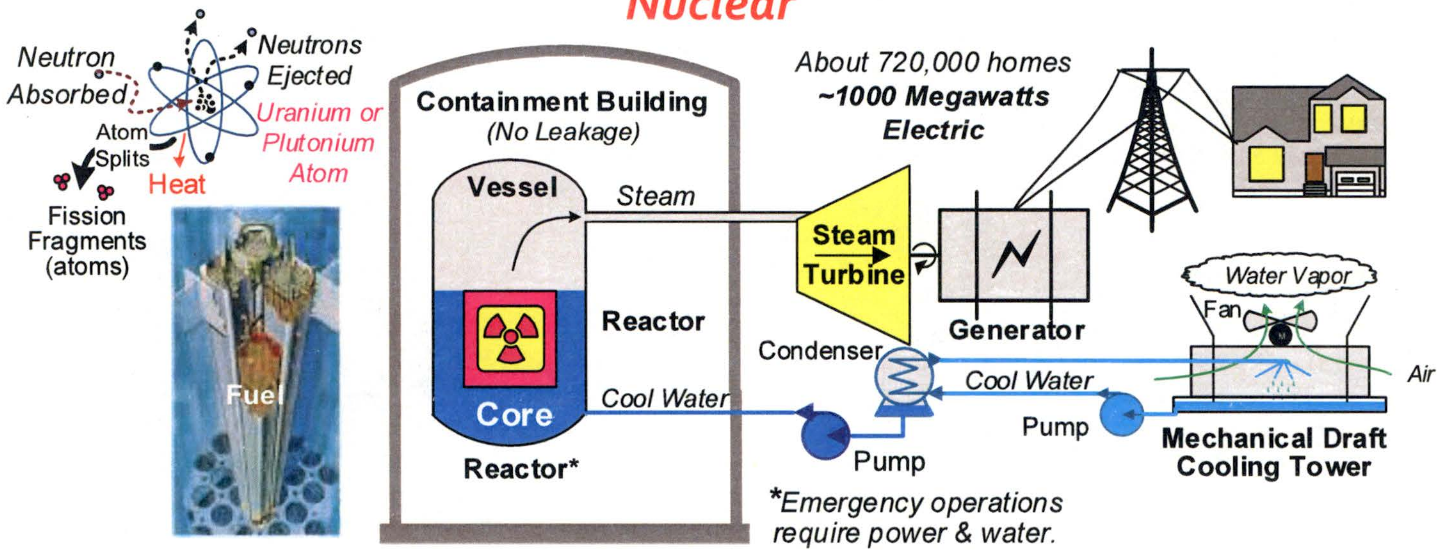
BACKGROUND: *Conventional*

/Nuclear Plant – *Boiling Water*

➢ **METAL TUBE REACTOR**

- Water Cooled & Moderated *(Neutrons slowed-down)*
- Core Boils Water
- Steam Rotates Turbine/Generator[1]
- Large Concrete & Steel Structures

Nuclear



Poor Energy Utilization
~34% Efficient

Worlds 1st
Commercial Boiling Water Reactor
Nuclear Power Station
1959 USA

CONCEPT

Note: *(1) Typical steam pressure & temperature +1000 psig/65 Bar & +570°F/300°C.*

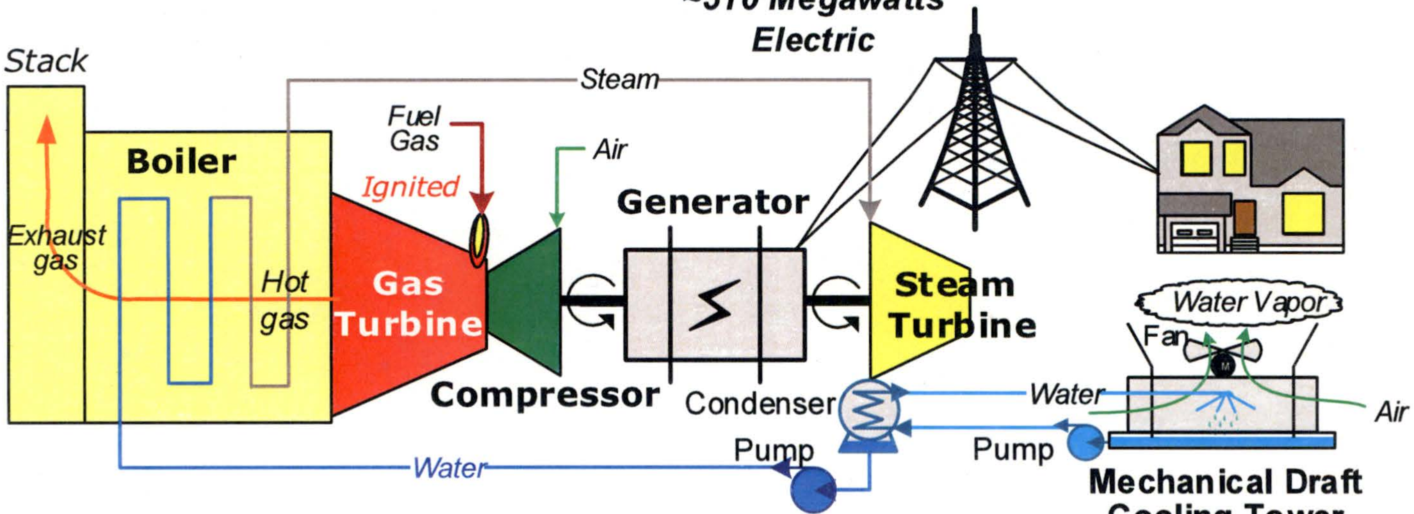
Hybrid-Nuclear Energy

BACKGROUND: *Conventional*
/Natural Gas Plant

➢ COMBINED-CYCLE[1]

- Air Pressurized, Mixed with Gas Fuel & Ignited
- Very Hot Gas Rotates Turbine & Boils Water
- Steam & Gas Turbines Rotate Generator
- Very Compact Power Plant

Gas



Significantly More Efficient than Coal
~55% versus ~36%

Worlds 1st
Commercial Combined-Cycle
Power Station
1961 Austria

<u>Notes:</u> ***(1)*** *Advanced Gas Turbine,* **Ref. 6**, *Higher Heating Value of natural gas. Typical gas firing temperatures +2600°F/1425°C & pressure +325 psig/22 BAR. Typical steam temperature & pressure +1000 °F/540°C & +1800 psig/120 BAR.* **(2)** *Steam turbine typically 50% of gas turbine's electrical output.*

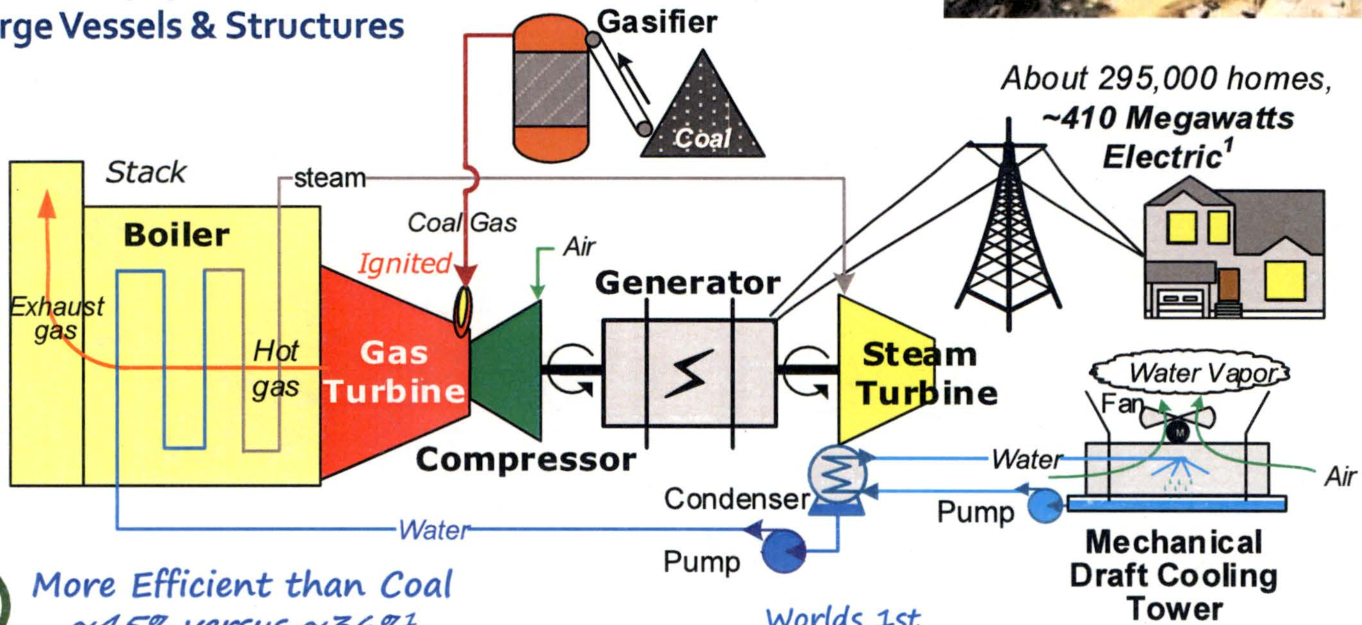
CONCEPT

BACKGROUND: *Conventional* /Coal-Gas Plant

➢ INTEGRATED COAL GASIFICATION

- Coal Converted into Gas
- Used with Combined-cycle[2]
- Gasifier Equipment – Large Vessels & Structures

Coal-Gas



More Efficient than Coal ~45% versus ~36%[1]

Worlds 1st Commercial Integrated Gasification Combined-Cycle Power Station 1994 Belgium

Notes: *(1) See* **Ref. 18**. *(2) Steam turbine typically ~80% of gas turbine's output. Gas turbine and steam turbine pressures & temperatures similar to those of combined-cycle.*

CONCEPT

BACKGROUND: *Grid Characteristics*

Hybrid-Nuclear Energy

Transmission Lines[1]

➢ POWER SOURCES SHOULD BE NEAR LOADS

✓ *Minimizes Costs*

Major Problem for Renewables[2]

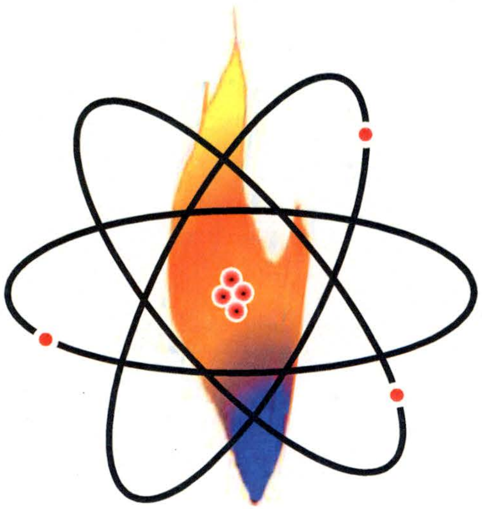
	69 KV	110 KV	230 KV	345 KV	500 KV	745 KV
New	~$280,000 /mile	~$500,000 /mile	~$1,000,000 /mile	~$1,3000.000 /mile	~$1,900,000 /mile	~$2,800,000 /mile
Width	50 ft. Wide	80 ft. Wide	125 ft. Wide	150 ft. Wide	175 ft. Wide	200 ft. Wide
Height	60 ft. High	75 ft. High	100 ft. High	125 ft. High	135 ft. High	150 ft. High
Span	~30 Mile Span	~35 Mile Span	~60 Mile Span	~110 Mile Span	~150 Mile Span	~500 Mile Span
Capacity	~50 MW	~125 MW	~400 MW	~850 MW	~1250 MW	~2200 MW
Losses	~1.6 MW(e)	~1 MW(e)	~12 MW(e)	~37 MW	~38 MW(e).	~110 MW(e).
Loss %	~10%	8%	5%	4%	2%	1%

Typical US Systems (230 KV – 345 KV)

~ 10% Power Loss per 100 Miles[1]

<u>Note</u>: *(1) Approximate installation values based on industry data. Typical upper limits on transmission line distance and capacity - rough costs per* **Ref. 27,** *single circuit line, relatively flat terrain. (2) In addition to higher line-loss costs caused by the renewables being well way from load centers, the intermittent nature of renewables causes inefficient use of transmission line capacity which causes higher prices due to debt and profit costs being distributed over reduced transmission line use as more reliable electrical generation is excluded.*

CONCEPT



Historical Perspective

During the early days of nuclear energy, numerous reactor types were investigated and built in the quest to develop economically viable power plants using the essentially unlimited energy available from splitting the atom. Reactor types included: water cooled, gas cooled, liquid metal cooled, fluid-fueled – **Ref. 24**.

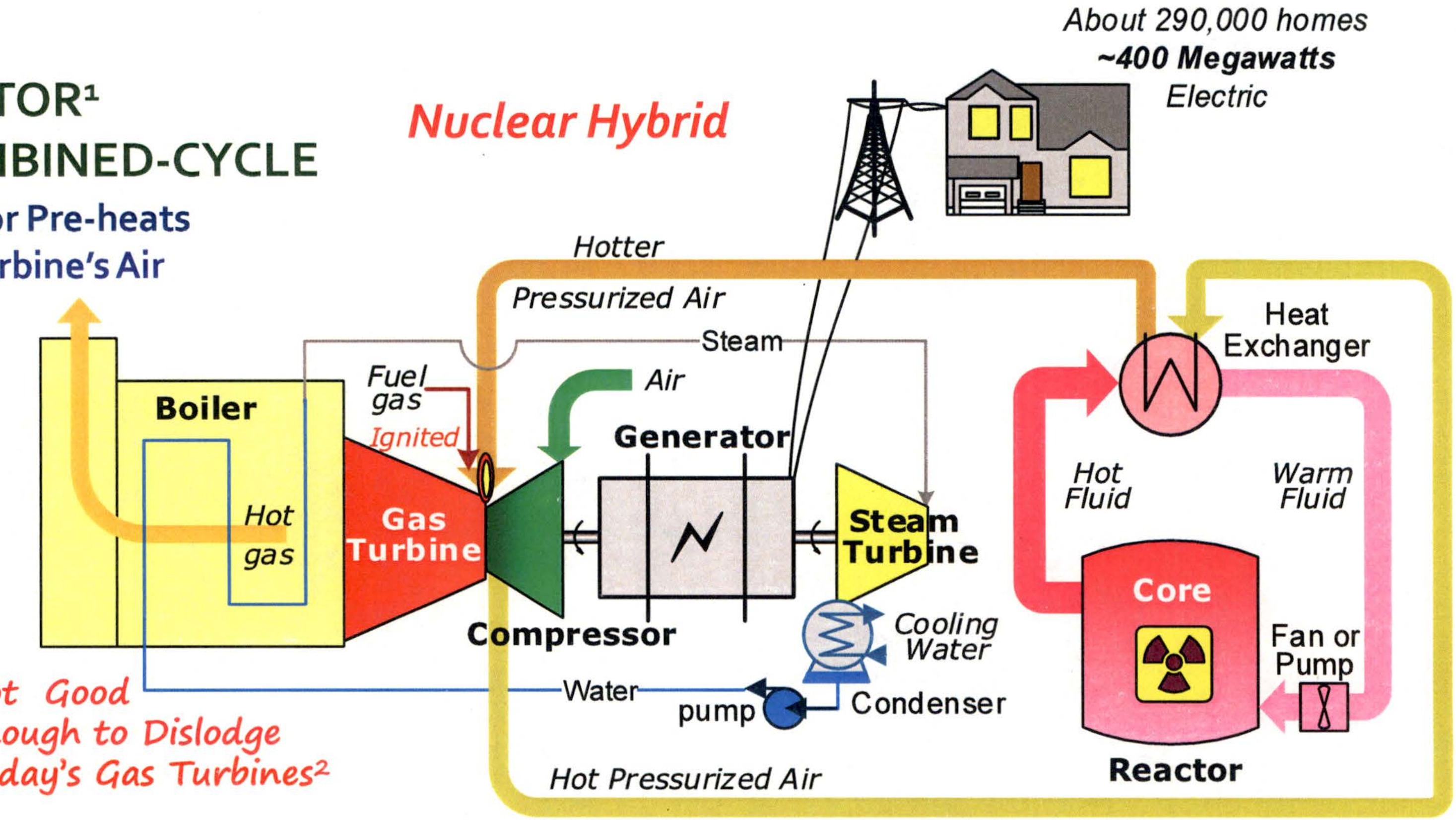
Today, major efforts are underway to resurrect various reactor concepts initially developed in the 1940's and 1950's but discarded for various reasons - generally financial. However, the ultimate success of today's advanced reactor "reboot" remains in doubt due to fundamental competiveness issues.

Today's gas turbines are approaching the upper limits of development as the ability of materials to tolerate very high temperatures is being heavily challenged - **Ref. 25** .

Conventional wisdom suggests that the technology of traditional electrical energy production has reached the point of diminishing returns typically associated with mature technologies. However, such an assessment is not accurate.

HYBRID: *Conventional*

➢ REACTOR[1]
+ COMBINED-CYCLE
- Reactor Pre-heats Gas Turbine's Air

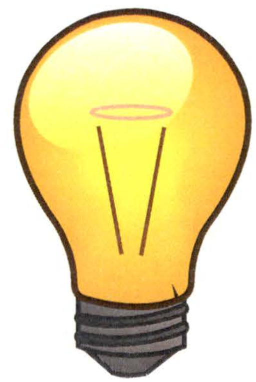


Not Good Enough to Dislodge Today's Gas Turbines[2]

Somewhat more Efficient than Combined-cycle
~60% fossil fuel use versus ~55%

CONCEPT

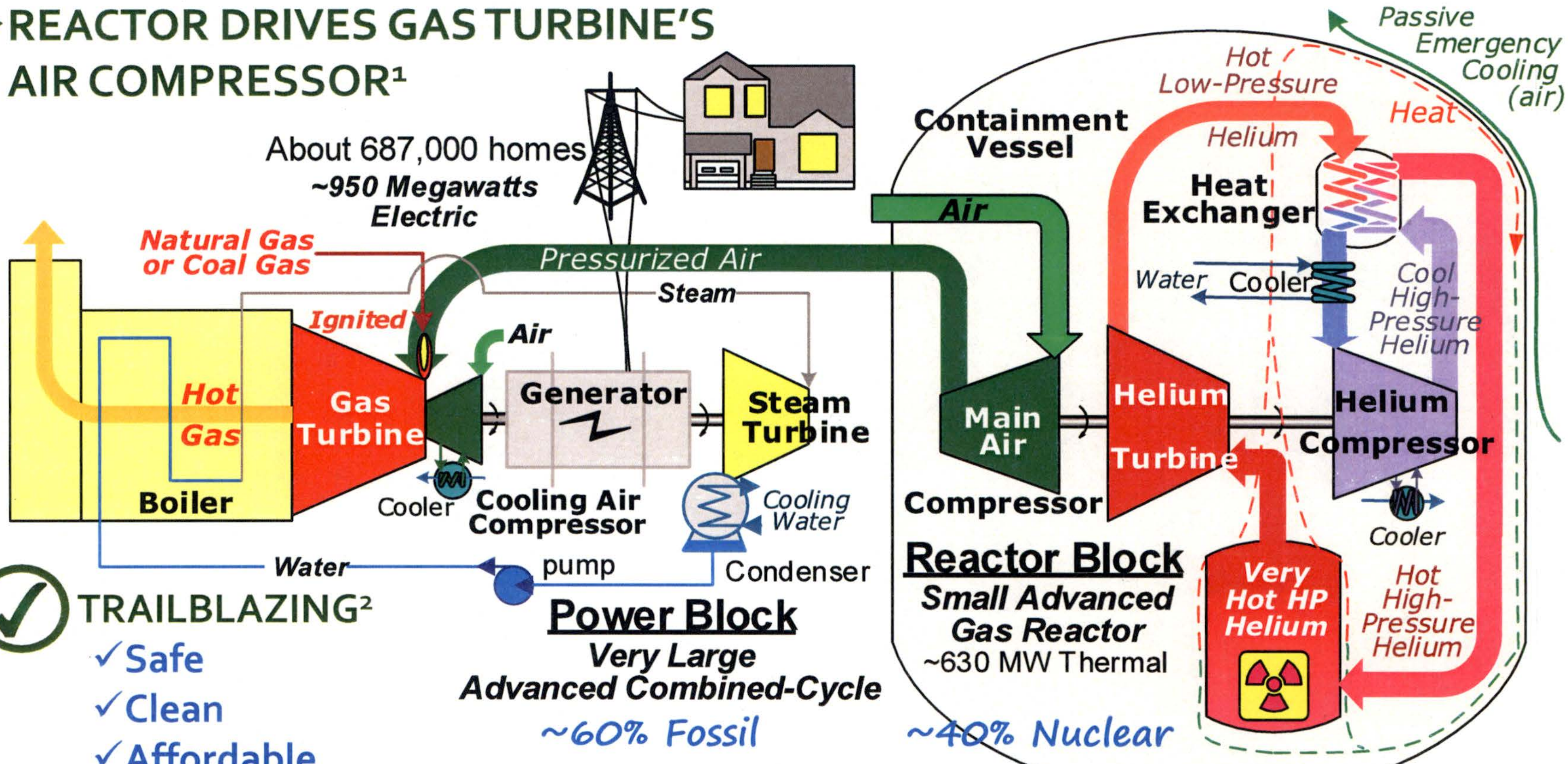
Note: ***(1)*** *Reactor typically gas, liquid salt or liquid nuclear fuel with output of a few hundred megawatts (thermal).* ***(2)*** *See chapter End-notes, item* ***A*** *for discussion of shortfalls.*



Eureka !

- *About Half of Gas Turbine's Power Used to Compress Air*
- *Roughly 15% of Air Used to Cool Machine*

➢REACTOR DRIVES GAS TURBINE'S AIR COMPRESSOR[1]



US Patents
7,961,835, 8,537,961

TRAILBLAZING[2]

- ✓Safe
- ✓Clean
- ✓Affordable
- ✓Readily Licensed
- ✓Numerous Uses
  - Profitable
  - Multi $Billion Markets

~Doubles Electrical Output[5]
+80% Fossil Fuel Efficiency
Peaking output ~1020 Megawatt electric[6]

New innovative approach to energy production

Notes: ***(1)*** *Process description, Chapter End-notes, item* ***B.*** ***(2)*** *Advantages summary, chapter End-notes, item* ***C*** ***(3)*** *Exergy - See Chapter End-notes, item* ***D.*** ***(4)*** *Steam turbine ~1/4th gas turbine output.* ***(5)*** *Uses 1 gas turbine to achieve output of 2 gas turbine plant.* ***(6)*** *Gas burners duct firing in boiler increase steam production for peaking.*

CONCEPT

The HYBRID: *Contrast*

STUNNING ADVANCEMENT[1]

- ✓More Competitive
- ✓More Powerful
- ✓Cleaner
- ✓Safer

Outdated

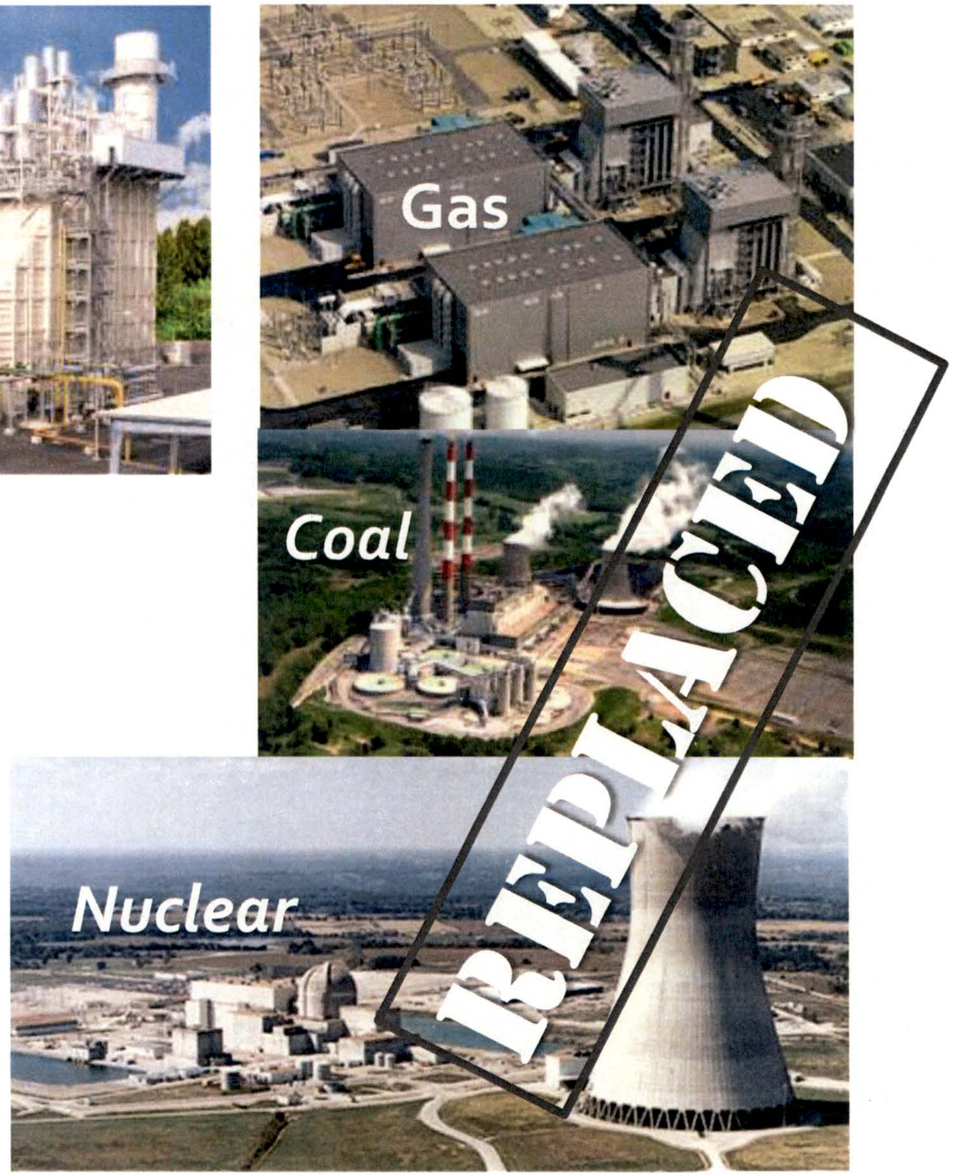
CONVENTIONAL

Note: ***(1)****. Today, two gas turbines (in combined-cycle configuration) can produce nearly 1000 MW(e), a feat that just ten years ago would have required three (or more) machines. Economics is the driver behind this continuing quest for ever more powerful machines. The Hybrid remains on this evolutionary path but is a major quantum leap because a single gas turbine can now provide the target 1000 MW(e) output.*

CONCEPT

The HYBRID: *Contrast*

20th Century



➢ 21st CENTURY ENERGY SOLUTION

✓ Practical New Direction
- Power Generation
- Nuclear Energy

✓ Genuine Hybrid*
- Not Self-styled

** Hybrid = two or more energy sources jointly providing useful work.*

CONCEPT

The HYBRID: *End-notes*

A. *Nuclear Hybrid*. *From a gas turbine's viewpoint, nuclear pre-heating of combustion air is not necessarily that useful. Air discharged from the compressor is already hot (typically +800°F/427°C). Practical considerations (e.g. metallurgy, thermal expansion effects, etc.) limit the use of nuclear heat to modest temperatures (~1400°F/760°C). Further, the plant's output is reduced covering reactor electrical loads. Even with very high firing temperatures (+2900°F/1600°C), the incremental gain is not sufficient enough to overcome high capitals cost of the reactor and complications of moving very hot reactor fluids.*

B. *Hybrid Process Overview.* *Nuclear reactor heats pressurized helium sent to turbine that rotates helium compressor and air compressor. Pressurized air mixed with fuel & ignited to spin gas turbine that rotates electrical generator. Turbine's hot exhaust boils water to rotate steam turbine also attached to generator.*

C. *Hybrid Advantages.* *The hybrid is a quantum leap improvement in combined-cycle power plant technology. A number advancements and innovations result, as outlined below:*

- ***Environmental***. *Dramatic reductions in environmental impacts as a result of joint use of fossil and nuclear energy.*
- ***Financial***. *Significant benefits to both consumers and investors due to the hybrid's impressive economies-of scale (large output, high-efficiency, low build cost) and marriage of the best features of nuclear and fossil technologies.*
- ***Applications***. *Many uses are possible because the hybrid is a more multi-purpose variation on the already versatile combined-cycle power plant.*
- ***Technical.*** *Numerous simplifications and improvements occur because the hybrid's new thermodynamic cycle allows the practical coupling of proven technology approaches.*
- ***Safety***. *Dramatic leap in public protection occur because the hybrid's fully passively fail-safe reactor. The hybrid is significantly safer than conventional reactors.*
- ***Regulatory***. *More rapid and cost effective licensing due to the hybrid' simplicity and exceptional level of safety.*

D. *Gas Turbine Exergy.* *The useful energy (exergy) available to gas turbines is heavily impacted by the power required to compress the working fluid (typically air). This energy loss is roughly 1/2 that produced by the turbine. The Hybrid relies on an efficient gas reactor for air compression and efficient turbine cooling which leads to stunning advancements.*

The chapters that follow provide more in-depth discussions of the hybrid technology.

USES

Historical Perspective

Both fossil and nuclear fuels are used by modern civilizations. However, fossil fuels (including coal) have significantly more diverse applications owing to their abundance, ease of fuel transport, relatively straightforward nature of the machines, and practical ability to produce readily usable co-products.

Nuclear power's applications are primarily limited to electrical generation as a result of limitations associated with the relatively low operating temperatures coupled with the presence of highly radioactive materials. Such complexities stymie expanding the commercial uses of the energy resource. However, that is no longer the case.

USES: *Summary*

➢ **EXCEPTIONALLY VERSATILE**

✓ *Far Exceeds Conventional Nuclear*

➢ **INNOVATIVE**

Conventional
- *Coal*
- *Nuclear*
- *Gas*

Hybrid-Nuclear Equivalents

➢ **ENERGY FREEDOM**

All US Fuels

No Uranium Imports

➢ **US PREMIER SUPPLIER**  **ENERGY**

✓ *Free world no longer intimidated by hostile energy suppliers*

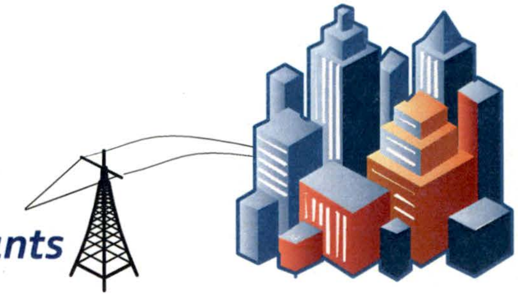
CONCEPT

USES: *Overview*
/Multipurpose

Hybrid-Nuclear Energy

✓Power & Co-Generation[1]

Large & Small Hybrid Energy Plants



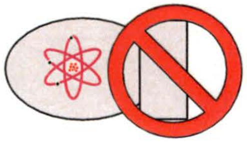
~15 mW (e) to + 1050 mW (e)

✓Fuels & Chemicals

Hybrid-Nuclear /Coal Gasification

- *Reactor supplies compressed air to manufacture synthetic compounds*

✓Stops Proliferation

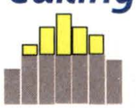


(Too Hard to Reprocess Fuel) + ***Plutonium Phase-out***

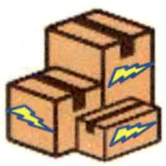
Thorium Fuel Cycle

✓Grid Support

Peaking



Baseload



Energy Storage

Renewables

Hybrids Highly Maneuverable

✓Isotopes

Medical

(½ $Billion/year industry)

Department of Defense

CONCEPT

Notes: *(1) Process steam, compressed air, chilled water, desalination, etc.*

USES: *Product Lines*
/ 21st Century Hybrids

OUTPUT Megawatt (electric)				
Micro-Hybrid/ All-Nuclear	Small-Hybrid/ All-Nuclear	Hybrid/ All-Nuclear	Hybrid/Gas & Coal-Gas	Advanced Hybrid/Gas & Coal-Gas
5				
15				
25	*Small Grids*			
45				
Remote Locations	120			
	170	*No Fossil Fuels*		
		320		*Large Grids, Chemical Production*
			+950	
				+1070

CONCEPT

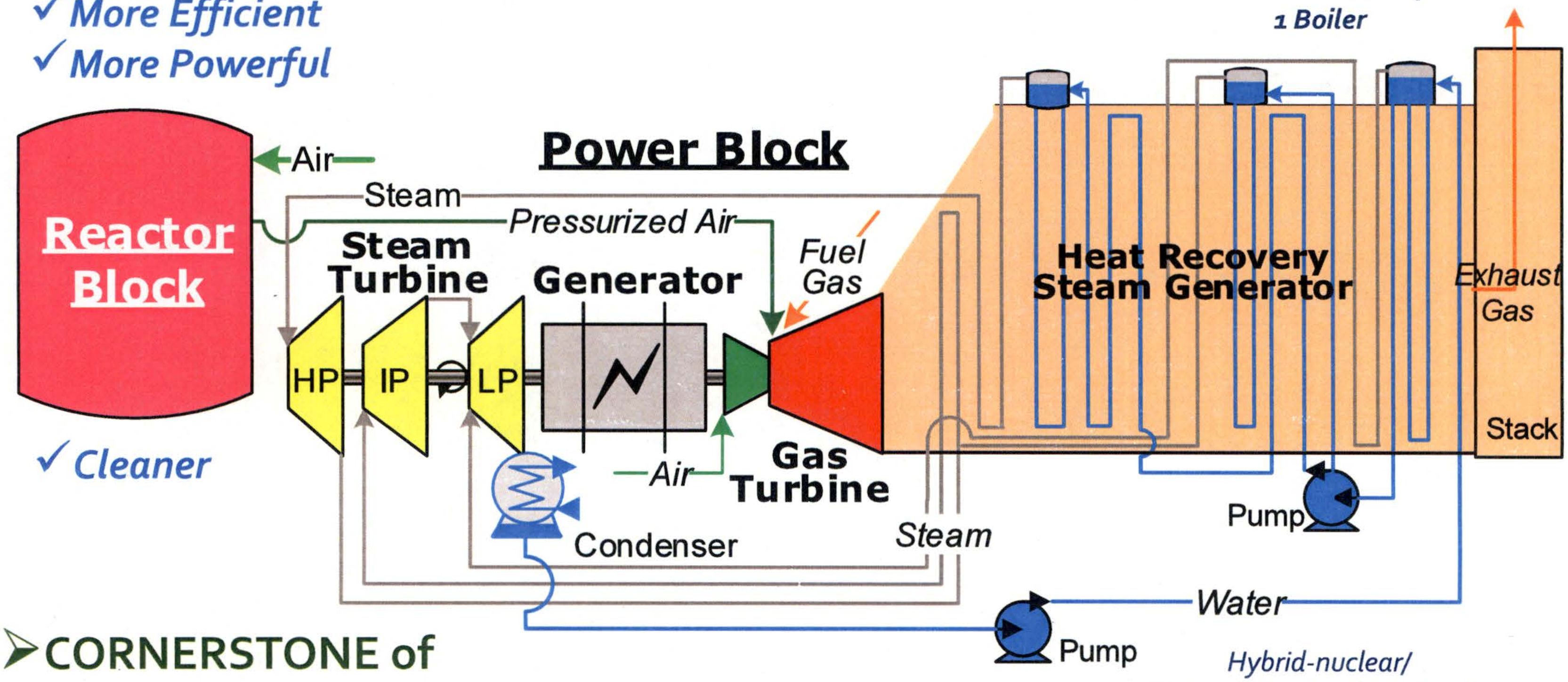
Note (1) *See* **APPENDIX F** *for HYBRID/All-nuclear overview.*

USES: *Power*
/Natural Gas

- ➢ REPLACES COMBINED-CYCLE
  - ✓ *More Efficient*
  - ✓ *More Powerful*
  - ✓ *Cleaner*

HYBRID/ Gas

~950 MW Electric, MW(e)
1 Generator,
1 Gas Turbine,
1 Steam Turbine,
1 Boiler



Hybrid-nuclear/ Natural Gas Combined-cycle {Hybrid/NGCC}

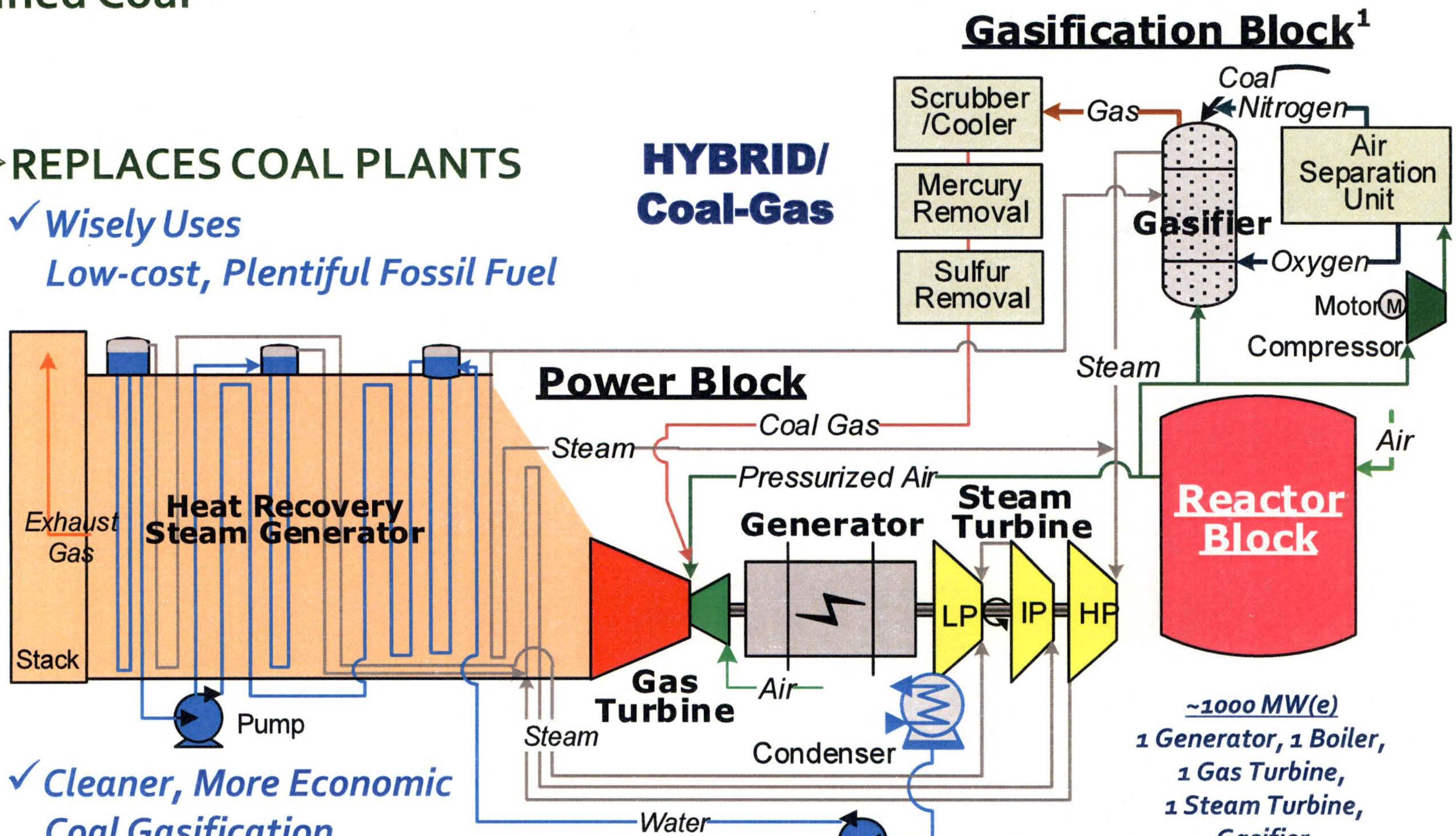
- ➢ CORNERSTONE of HYBRID-NUCLEAR FAMILY

CONCEPT

USES: *Power* /Gasified Coal

➢ REPLACES COAL PLANTS

✓ *Wisely Uses Low-cost, Plentiful Fossil Fuel*



✓ *Cleaner, More Economic Coal Gasification*

✓ *Half the Size, Twice the Output*

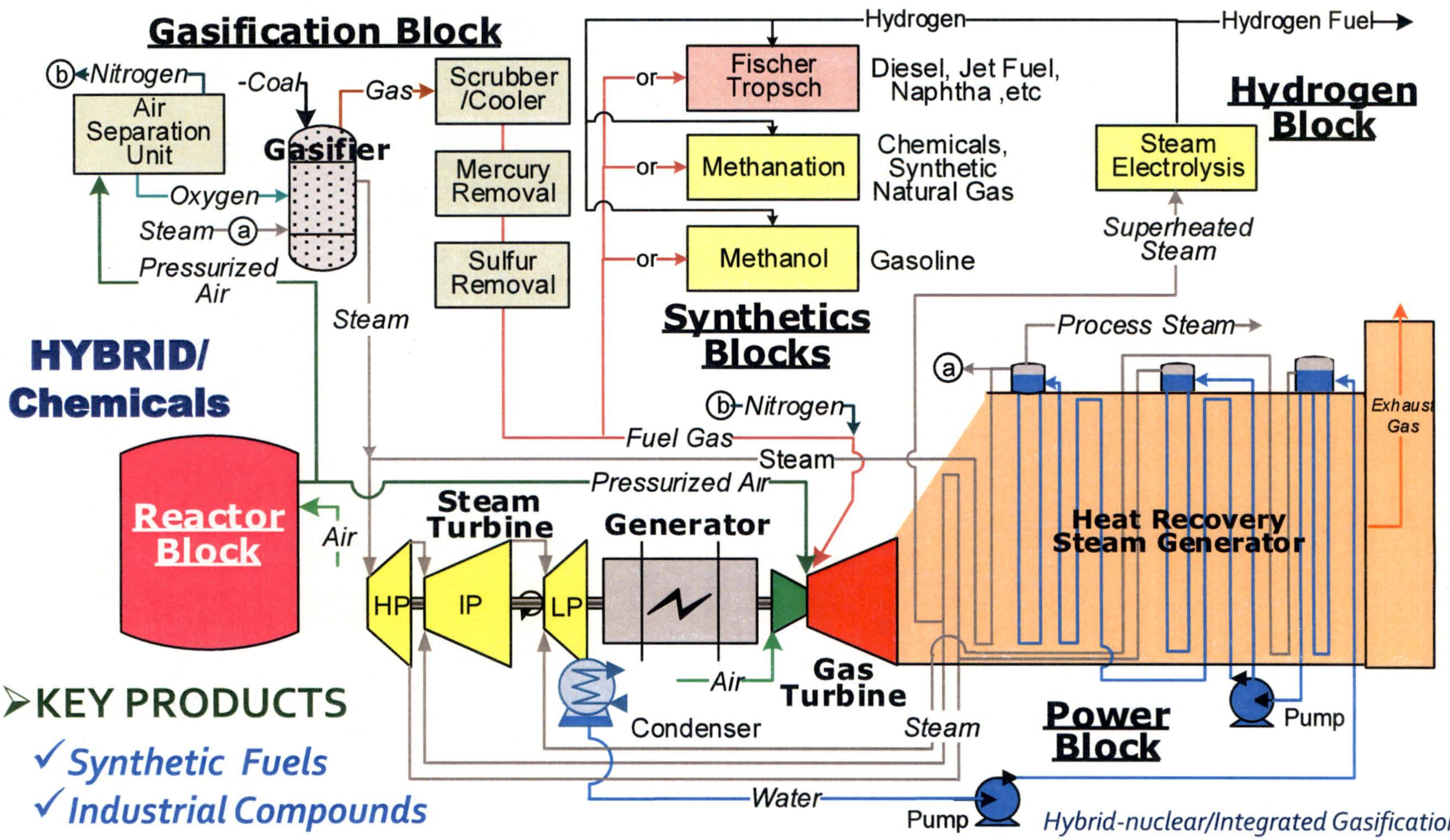
Hybrid-nuclear/ Integrated Gasification Combined-cycle ***{Hybrid/IGCC}***

~1000 MW(e)
1 Generator, 1 Boiler, 1 Gas Turbine, 1 Steam Turbine, Gasifier (~ 80% efficient coal energy use)

Note: *(1) Gasification equipment about ½ the size of a conventional coal-gas plant with similar power output. Emissions are significantly reduced relative to conventional IGCC plants.*

CONCEPT

USES: *Process Industry*



➤**KEY PRODUCTS**

✓ *Synthetic Fuels*

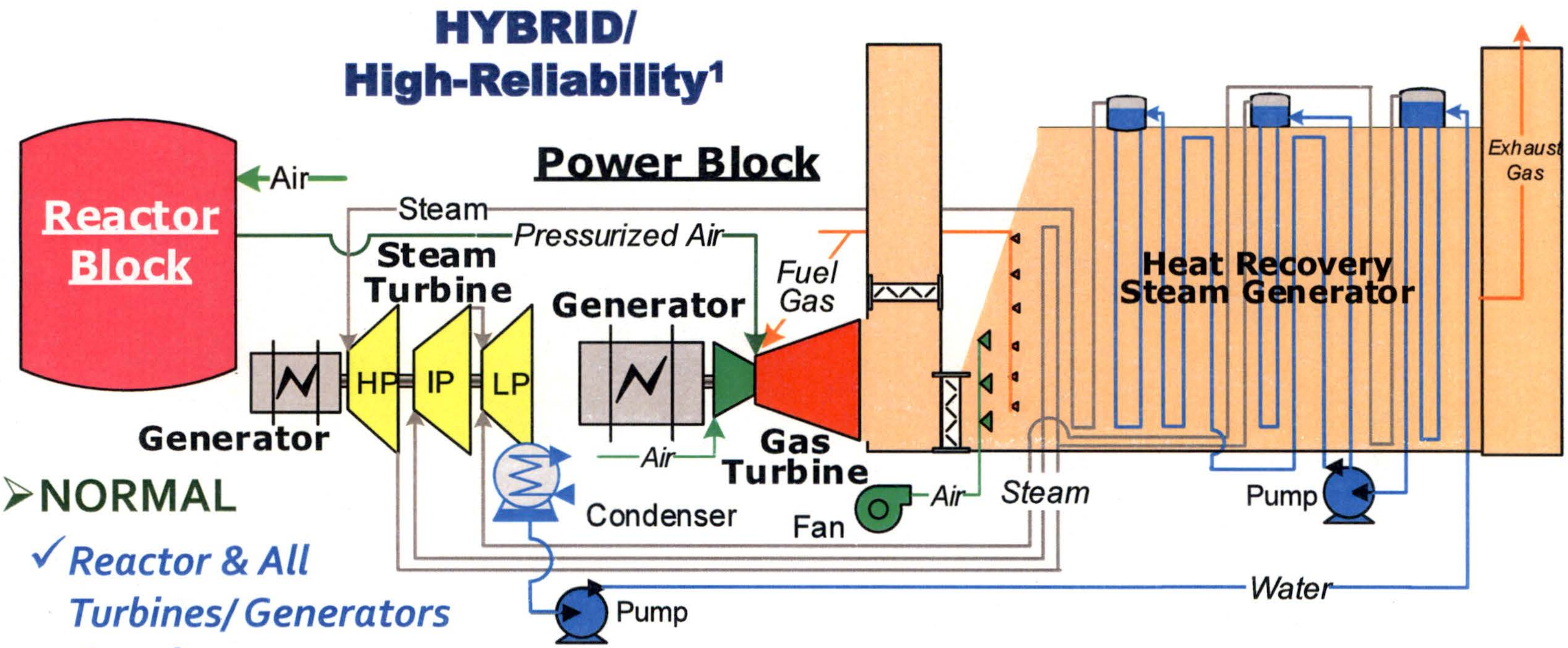
✓ *Industrial Compounds*

Hybrid-nuclear/Integrated Gasification Combined-cycle/Coal-to-Liquids & Gases[2]
{Hybrid/IGCC/CTLG}

Note: *(1) Gasification equipment about ½ the size of a conventional coal-gas plant with similar power output. (2) Coal gasification plants are routinely used throughout the world to produce a wide variety of synthetic fuels, chemicals, fertilizers, liquefied gases, etc. The processes, however, produce noteworthy air pollution as well as greenhouse gases. The Hybrid/Chemicals plants significantly reduces these emissions.*

CONCEPT

USES: *High Availability*
/Option - *All Configurations*



➢NORMAL

✓ *Reactor & All Turbines/ Generators Running*

➢REACTOR "Off"

✓ *Boiler, Fans & Steam Turbine/Generator Running*

<u>Notes</u>: *(1) Bypass stack & separate steam turbine allow highly flexible plant operation:*

- *Boiler + Steam Turbine/Generator: ~ 200 MW(e).*
- *Reactor + Gas Turbine/Generator: ~ 750 MW(e), bypass stack "on", boiler "off"*
- *Reactor + Gas Turbine/Generator + Boiler + Steam Turbine/Generator: ~950 MW(e), plant. Plant readily swings between gas turbine "on" and fan "on" with boiler "on".*

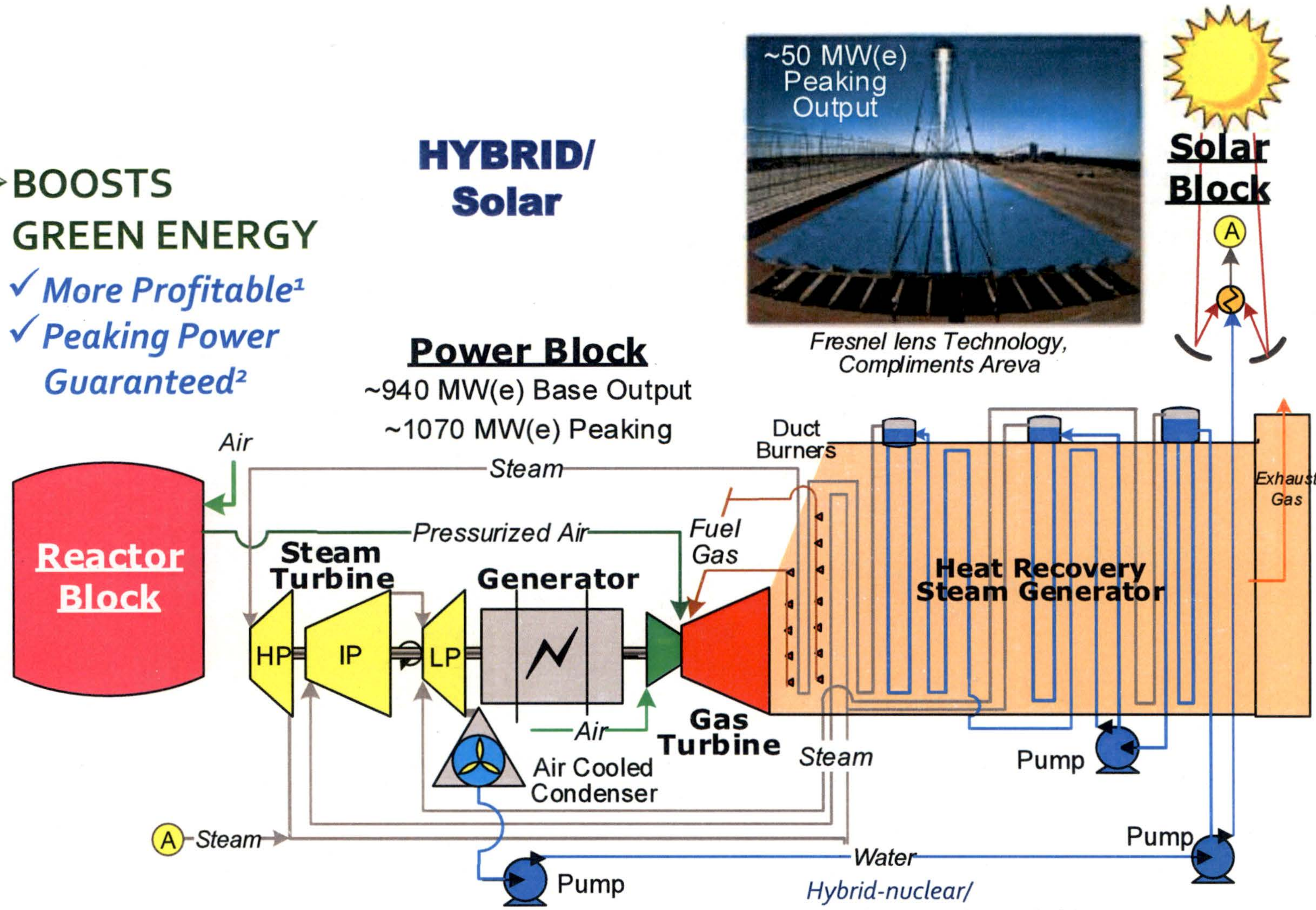
This variation on a combined-cycle plant is in use today, typically at refineries where reliable steam & power are critical needs.

CONCEPT

USES: *Solar Support*

- ➢ BOOSTS GREEN ENERGY
  - ✓ *More Profitable*[1]
  - ✓ *Peaking Power Guaranteed*[2]

HYBRID/ Solar



Hybrid-nuclear/ Integrated Solar Combined-cycle[2] ***{Hybrid/ISCC}***

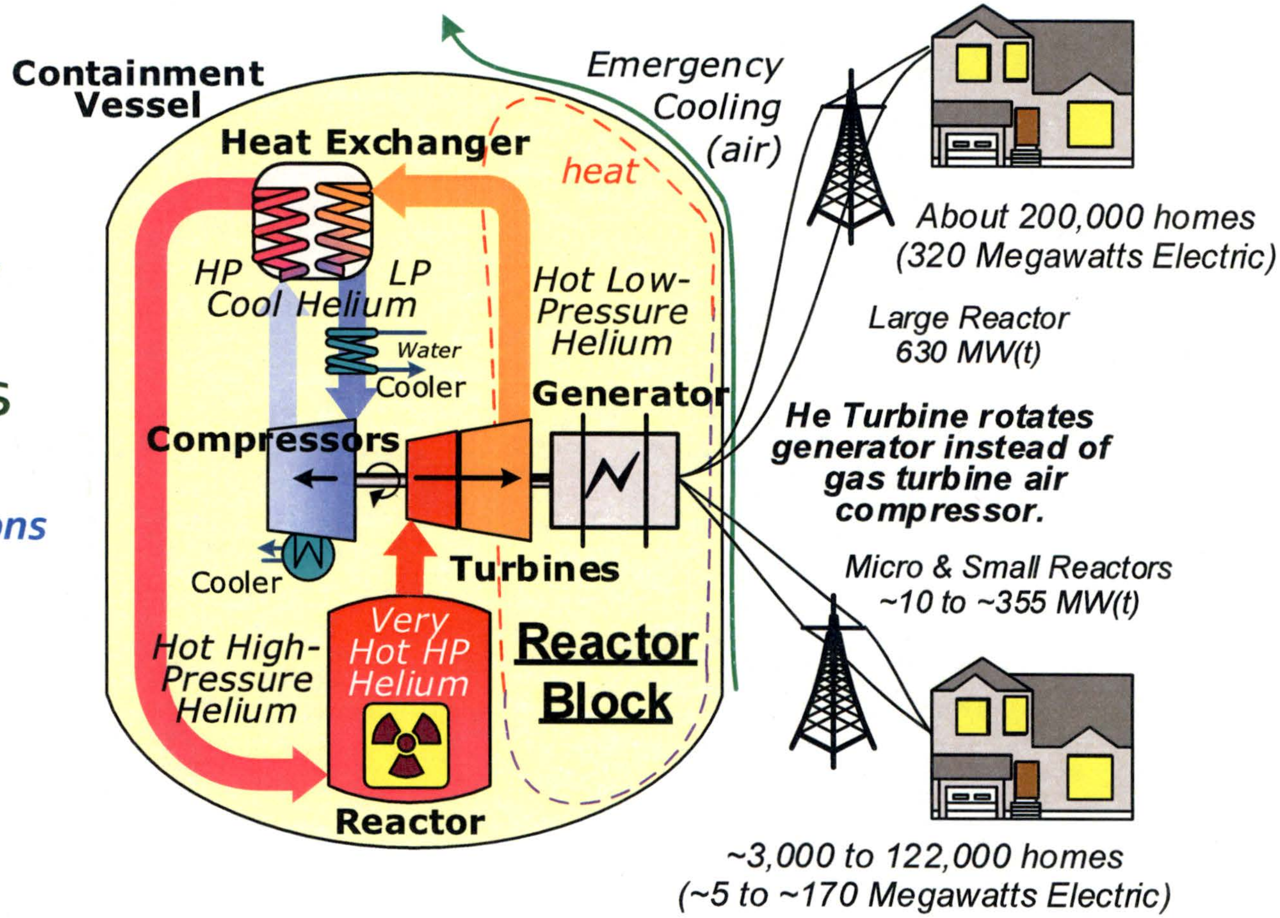
Notes: ***(1)*** *Number of ISCC plants are in use in Middle East, e.g. the Waad Al Shamal in Saudi Arabia. More cost effective than stand-alone solar power plant.* ***(2)*** *Duct burners cover intermittent loss of solar.*

CONCEPT

USES: *Special Situations*
/No Fossil Fuels Available

HYBRID/ All-Nuclear

- UNIQUE NEEDS SOLUTIONS[1]
  - ✓ *Remote Locations*
  - ✓ *Military Bases*
  - ✓ *Islands*



CONCEPT

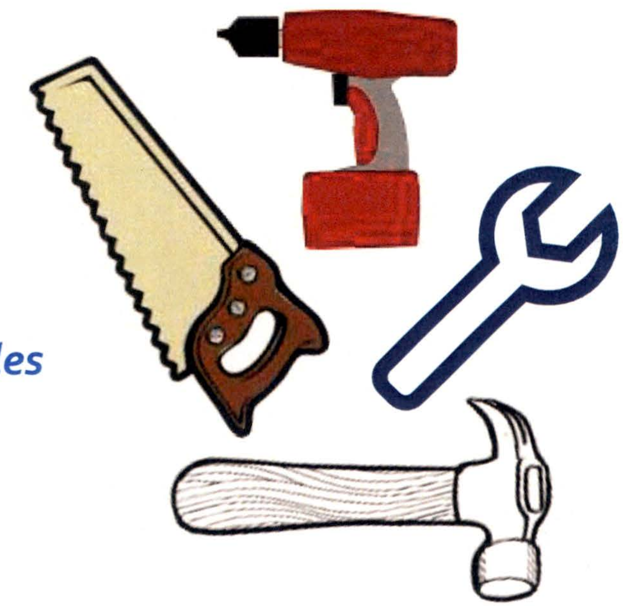
Note (1) *See* **APPENDIX G** *for HYBRID/All-nuclear overview.*

USES: *Grid Reliability**

HYBRID/ Grid-Support

➢VERSATILE

✓ *Readily Accommodates Grid & Renewables*
- Financially[1]
- Technologically[2]



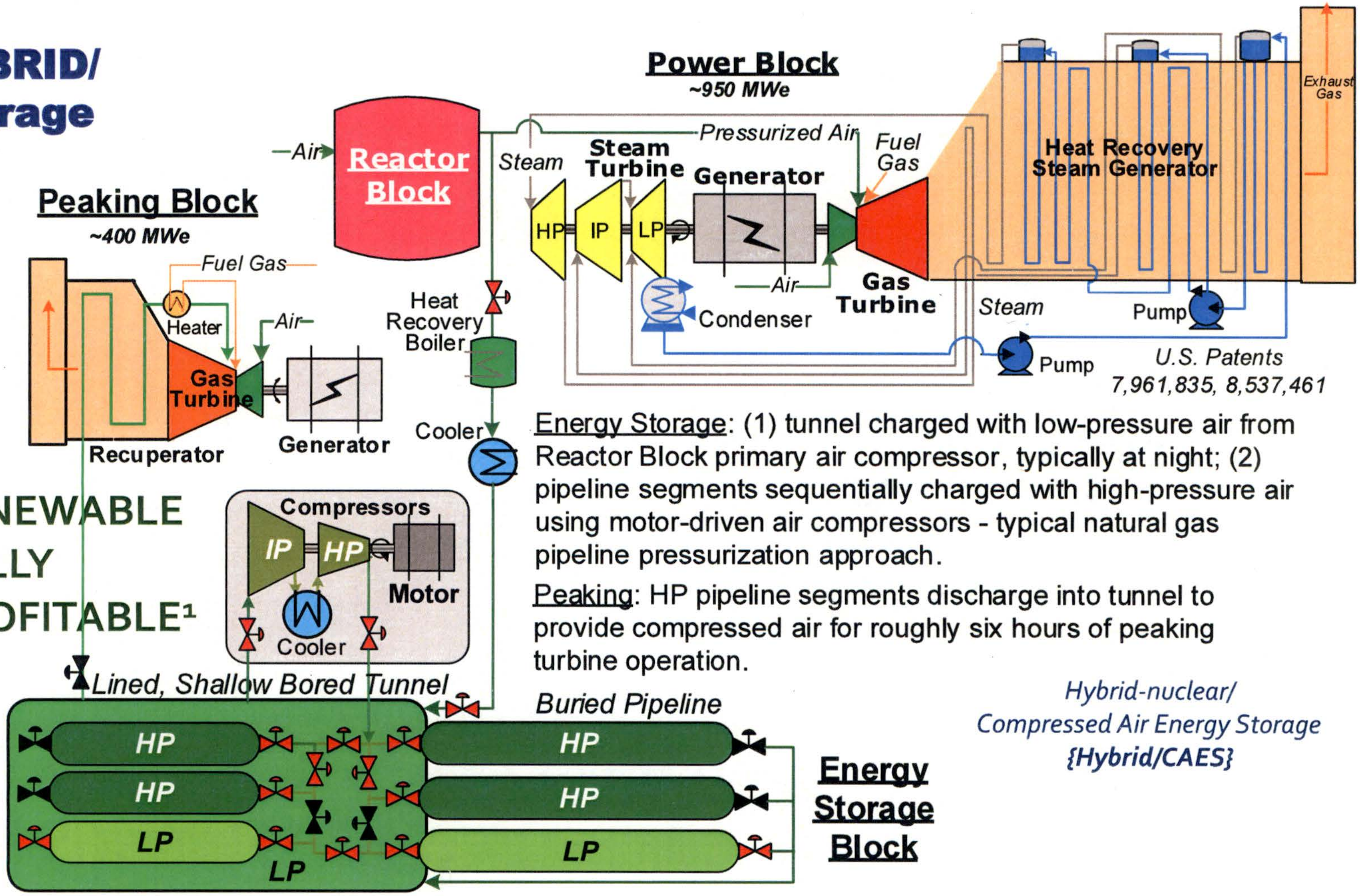
* *Voltage & frequency control to maintain grid stability and efficiency in response to load demand or generation supply changes.*[3]

<u>Note:</u> *(1) See* **FINANCIAL**: *Contrast/* Energy Cost & Returns". *(2) See* **TECHNOLOGY**: *Control. (3) From an electrical engineering standpoint, the unit Volt-Ampere Reactance (VAR) is a measure of the degree to which volts and amps are out of phase in an alternating current circuit. While such imbalances create money wasting inefficiencies, revenue opportunities are also created for technologies that can counteract the inefficiency. Additional revenue opportunities are also created for technologies that can maintain the grid within required frequency and voltage levels. Such levels are essential for the proper operation of modern electrical machinery and electronics.*

CONCEPT

USES: *Energy Storage*
/"Green" Energy & Peaking Support

HYBRID/ Storage



➢ RENEWABLE FULLY PROFITABLE[1]

Energy Storage: (1) tunnel charged with low-pressure air from Reactor Block primary air compressor, typically at night; (2) pipeline segments sequentially charged with high-pressure air using motor-driven air compressors - typical natural gas pipeline pressurization approach.

Peaking: HP pipeline segments discharge into tunnel to provide compressed air for roughly six hours of peaking turbine operation.

Hybrid-nuclear/ Compressed Air Energy Storage ***{Hybrid/CAES}***

Notes: *(1) Surplus renewable electricity (which is otherwise sold at a loss) used to help power motor driven air compressors.* ***(2)*** *Fossil fuel efficiency ++85% versus peaking gas turbine ~35%.*

CONCEPT

USES: Radioactive Sources

HYBRID/ Isotopes

➤ PROFITABLE SIDE-BAR BUSINESS

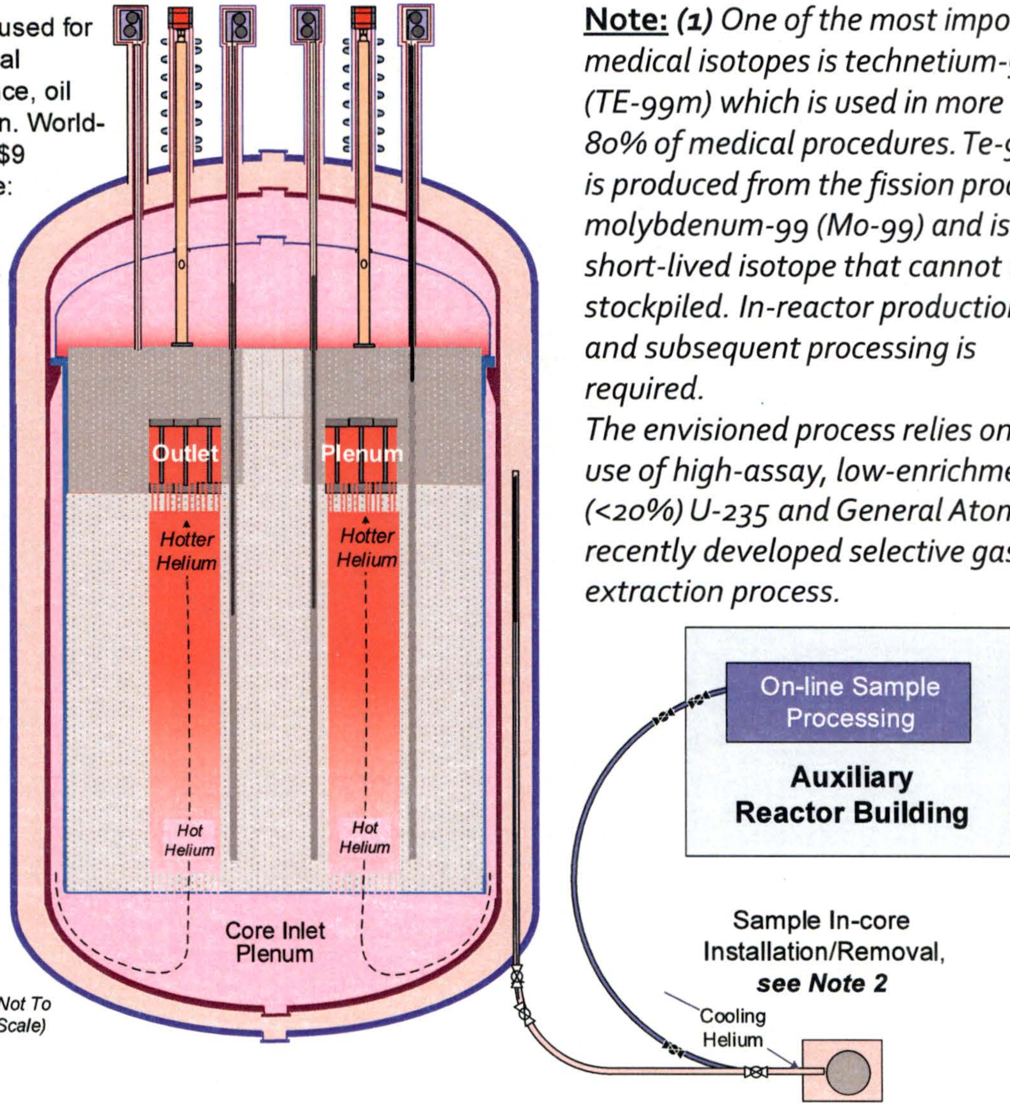
✓ *$100's of millions*

Important Isotopes are used for medical research, clinical nuclear medicine, science, oil exploration, construction. World-wide demand exceeds $9 billion. Isotopes include:

- Americium-241
- Californium-252
- Molybdenum-99 *
- Actinium-225
- Uranium-232
- Gagolinium-153
- Promethium-147
- Copper-67
- Astatine-211
- Tin-117m
- Zirconium-89

Tritium is an isotope vital to national defense and is produced by lithium absorbing a thermal neutron.

**See Note 1*



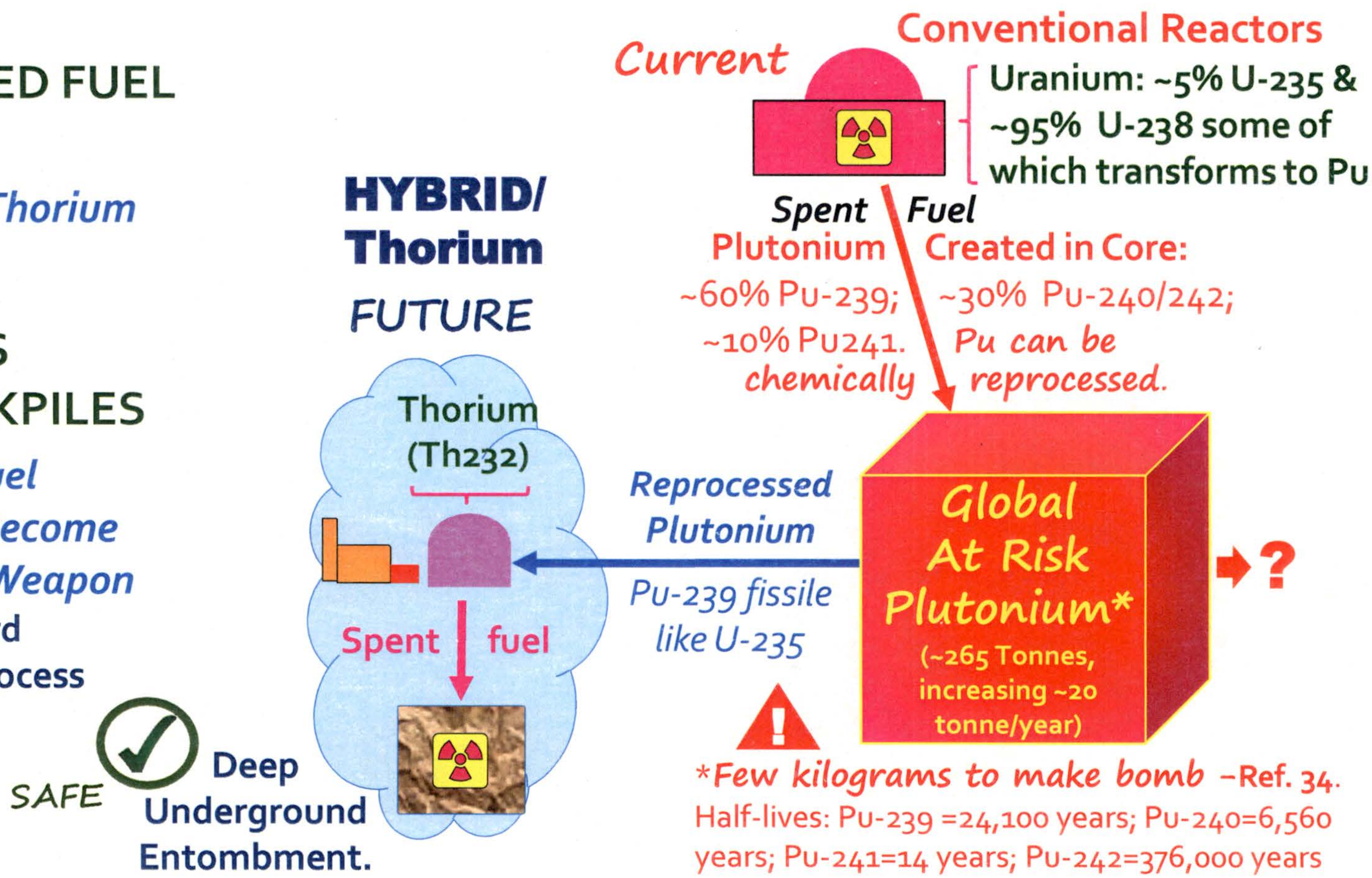
Note: **(1)** *One of the most important medical isotopes is technetium-99m (TE-99m) which is used in more than 80% of medical procedures. Te-99m is produced from the fission product molybdenum-99 (Mo-99) and is a short-lived isotope that cannot be stockpiled. In-reactor production and subsequent processing is required.*
The envisioned process relies on the use of high-assay, low-enrichment (<20%) U-235 and General Atomics' recently developed selective gaseous extraction process.

Notes **(2)** *The on-line process is based on the moveable in-core detector technology routinely used by conventional nuclear power reactors*

CONCEPT

USES: *Plutonium Phase-out*

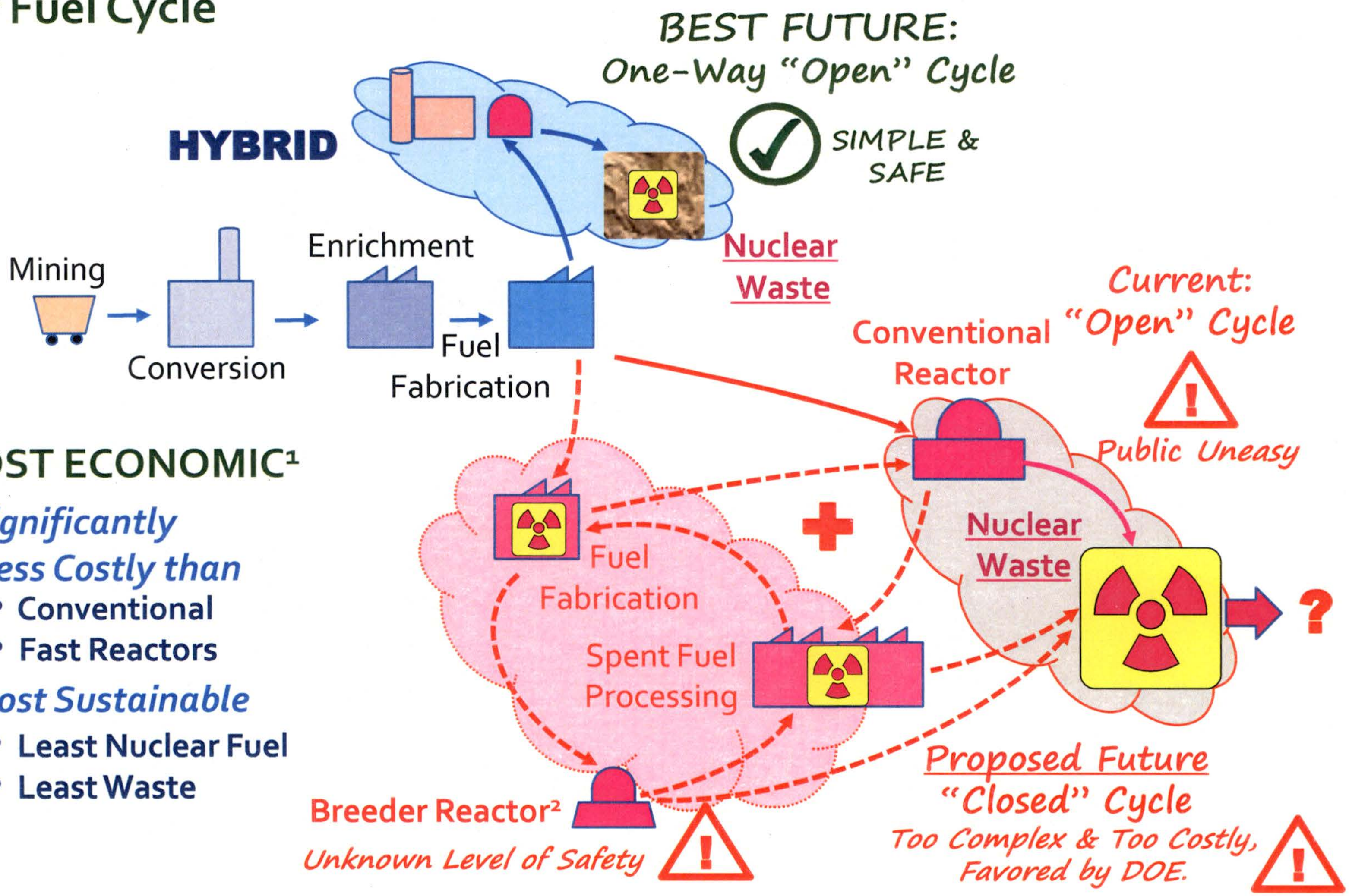
- **UNLIMITED FUEL SUPPLY**[1]
  - ✓ *Massive Thorium Reserves*
- **REDUCES Pu STOCKPILES**
  - ✓ *Hybrid Fuel Cannot Become Nuclear Weapon*
    - Too Hard to Reprocess



<u>**Note:**</u> ***(1)*** *Hybrid's graphite core well suited for this application and nearly impossible to remove Pu or Th from Hybrid fuel. Thorium Cycle involves: (a) Pu-239 absorbing neutron to release energy; and (b) Th-232 absorbing neutron, transmuting to U233 which absorbs neutron to release energy. Advantages: (a) Thorium is much more abundant (factor of ~3) than Uranium and requires no enrichment ; (b) does not produce extremely long-lived toxic waste (e.g. Plutonium, Americium, Curium), like current Uranium fuel cycle. Thorium has been previously used in gas reactors -* **Ref. 32**.

CONCEPT

USES: *Contrast*
/Nuclear Fuel Cycle



➢MOST ECONOMIC[1]

✓ *Significantly Less Costly than*
- Conventional
- Fast Reactors

✓ *Most Sustainable*
- Least Nuclear Fuel
- Least Waste

Notes: *(1) Assessment developed from* **Ref. 30** *using simple overview of basic economics and engineering.* *(2) Breeder reactors (create more fuel than they use) are expensive & difficult undertakings –* **Ref 24.** *The Hybrid's one-way "open" cycle erases need for breeder reactors because the Hybrid's highly efficient use of nuclear, fossil fuels and renewables is sustainable.*

CONCEPT

USES: *Contrast*
/Grid Support

➢VERY GOOD

Capability[1]	HYBRID	*Gas*[5]	*Coal*[5]	*Nuclear*[5]	*Wind & Solar*[2]
Fuel Storage	Average[6]	*Average*[6]	*Good*[7]	*Best*[8]	*Poor*
Dependability	Good	*Good*	*Good*	*Good*	*Poor*
Minimum Power, % (MW(e))	~35% (330)	*~50% (~225)*	*~45% (~400)*	*~50% (~560)*	*Erratic*
Maneuvering, % /minute (MW(e)/minute)[13]	~10 % (~75)	*~10 % (~35)*	*~2 % (~25)*	*~1.5 % (~15)*	*Erratic*
Hot Start, minutes	<30	*<30*	*<190*	*<120*	*Erratic*
Proximity to Load Center[9]	Good	*Best*	*Maybe*[10]	*Doubtful*[11]	*Poor*[12]
VAR Grid Support	Good[3]	*Good*[4]	*Average*[4]	*Limited*[4]	*Poor*

Notes: *(1) Typical, single unit plant. (2) Greater use of unreliable renewable requires other plants to more rapidly respond, including providing reactance support to stabilize grid. (3) Very large VAR (reactance) capability: generator turning as motor; steam turbine de-clutched (not spinning); gas turbine spinning but not firing with secondary compressor cooling machine, and reactor plant shutdown. Gas plant would require additional clutch to disengage gas turbine from generator (to avoid over heating), but very large clutches not feasible. (4) Typically ~5 to 10% of generator output to avoid generator damage and lost revenue from non-unity power factors -* **Ref.21**. *(5) Gas & coal plant minimum power generally constrained by emission regulations -* **Ref. 9**. *(6) Requires availability of pipeline gas (although machines can run on diesel& jet fuel).Hybrid/Coal-Gas "Good" fuel storage. (7) Limited by fuel supply at plant. (8) All fuel stored at plant site. (9) Within ~20 miles. (10) Potential emissions problems, particularly NOx see Environment Chapter End-note, item* ***B***. *(11) See* **Safety** *chapter. (12) Large installations too land intensive and suitable renewable resources rare. (13) See Chapter end-notes item* ***A*** *for general discussion on maneuvering capabilities.*

CONCEPT

USES: *Rankings*
/Nuclear Plants

Category[1]	HYBRID	Gas Reactors	Water Reactors
Large Output	✓+	✗	☆
Chemicals & Fuels	☆	✗	✗
Proliferation	☆	✓	✗
Thorium Fuel Cycle	☆	☆	✗
Industrial Support[3]	☆	✓-	✗
Energy Storage	☆	✗	✗
Grid Support	☆	✓	✗
Total Uses	☆	✗+	✗
NET[2]	☆-	✗+	✗

- HYBRID MOST USEFUL
  - ✓ *Numerous Applications*

☆ *= Best,* ✓ *= Average,* ✗ *= Needs Work. See* ***Appendix A*** *for ranking method*

Notes: ***(1)*** *Scoring relative to each other.* ***(2)*** *Average of categories.* ***(3)*** *Steam, compressed air, chilled water, etc.*

CONCEPT

USES: *Rankings*
/Power Plants

Category[1]	HYBRID	*Gas*	*Coal*	*Nuclear*	*Solar & Wind*
Large Output	✓+	✓+	✓+	★	✗
Chemicals	★	✗	✓	✗	✗
Industrial Support[2]	★	✓+	✓+	✓	✗
Renewable Support[3]	★	★	✗	✗	✗
Grid Support	★	✓+	✗+	✓	✗
Total Uses	★	✓	✗+	✗	✗
NET[4]	★-	✓	✓	✗+	✗

★ = *Best,* ✓ = *Average,* ✗ = *Needs Work. See* ***Appendix A*** *for ranking method*

➢ **HYBRID MOST VERSATILE**

✓ ***Easily Meets Numerous Needs***

Notes: *(1) Category scoring relative to each other. (2) Steam, compressed air, chilled water, etc. (3) Ability to balance erratic nature of renewables. (4) Average of categories.*

CONCEPT

A.Maneuvering. *The energy output of a thermal power production process is proportional to mass flow through the machine multiplied by the temperature difference across the heat source. In order to change the machine's output, the mass flow, heat differential or both must be altered. The rate at which output can be changed is dependent on the capabilities of the particular type of machine. Further, the process efficiency varies dramatically, depending on the method used for actually altering output. Some machines are more adept at efficiently and rapidly accommodating load changes than others.*

Conventional pressurized water reactors typically employ fixed speed pumps which means power reductions require reducing the temperature differential across the core. Mechanical design restraints limit the rate at which changes can be made, including the net power change in a given time interval. Additionally, nuclear physics also place limitations on core power changes. Generally, conventional reactors can accommodate large daily load changes - 100% to 50% - **Ref. 21**. *However, very rapid changes associated with the large-scale presence of renewable energy are problematic owing to component mechanical stress (typically fatigue limits) issues. An alternative strategy is to bypass the turbine/generator by dumping steam to the condenser – this approach obviously wastes energy. Conventional water reactors are fundamentally base-load machines, particularly when considering the need to pay-off debt and the owner's expected investment return – see* **Financial** *chapter.*

Coal plant capabilities based on **Ref. 9.**

Gas turbines (open-system Brayton cycle) are inherently adept at quickly maneuvering owing to: (1) the use of moveable stators located at the compressor inlet - **TECHNICAL*: Control*** *; and (2) the ability to rapidly alter fuel flow thereby quickly changing heat source temperature differentials. The maneuvering rate is typically around 10% per minute -* **Ref. 26.** *While the machine's efficiency is reduced with lowering firing temperatures, combined-cycle plants are not overly impacted, with net efficiencies at a 60% load reduced by about 9% -* **Ref 25**.

Closed-system Brayton cycles are quite different from open cycles because the mass flow can be altered by simply adding or subtracting system inventory. The machine's efficiency is thus essentially constant over most of the operating range – **Ref. 22**. *The limitation then becomes primarily on how fast the heat source can accommodate temperature changes and the degree to which the system can be safely "emptied" without unduly affecting the heat source - reactor in this case.*

The control strategy for the Hybrid is based on employing the best elements of open and closed Brayton system. The gas turbine's inlet stator vane system is used for rapid response to grid requirements, moderately rapid needs are accommodated by directing helium around HP turbine – **TECHNICAL*: Thermal Cycle*** *and "mini-bypass of* **Ref. 22**. *Longer duration needs are provided by reactor's inventory control system –see* **TECHNICAL*: End-notes,*** *item G.*

ENVIRONMENT

Historical Perspective

The production of electrical power has always involved escalating conflict between economics and minimizing the degradation of the environment. Generally, pollution reductions occur through profit motivated technology innovations stimulated by government legislation associated with the broad recognition of the harmful affects of dumping material into the environment.

Some energy production methods are clearly better than others from a pollution standpoint but virtually no method has zero impact on the environment.

The ultimate environmental success of any energy production process lies with striking a reasonable balance between costs and undue impacts.

ENVIRONMENT: *Summary*

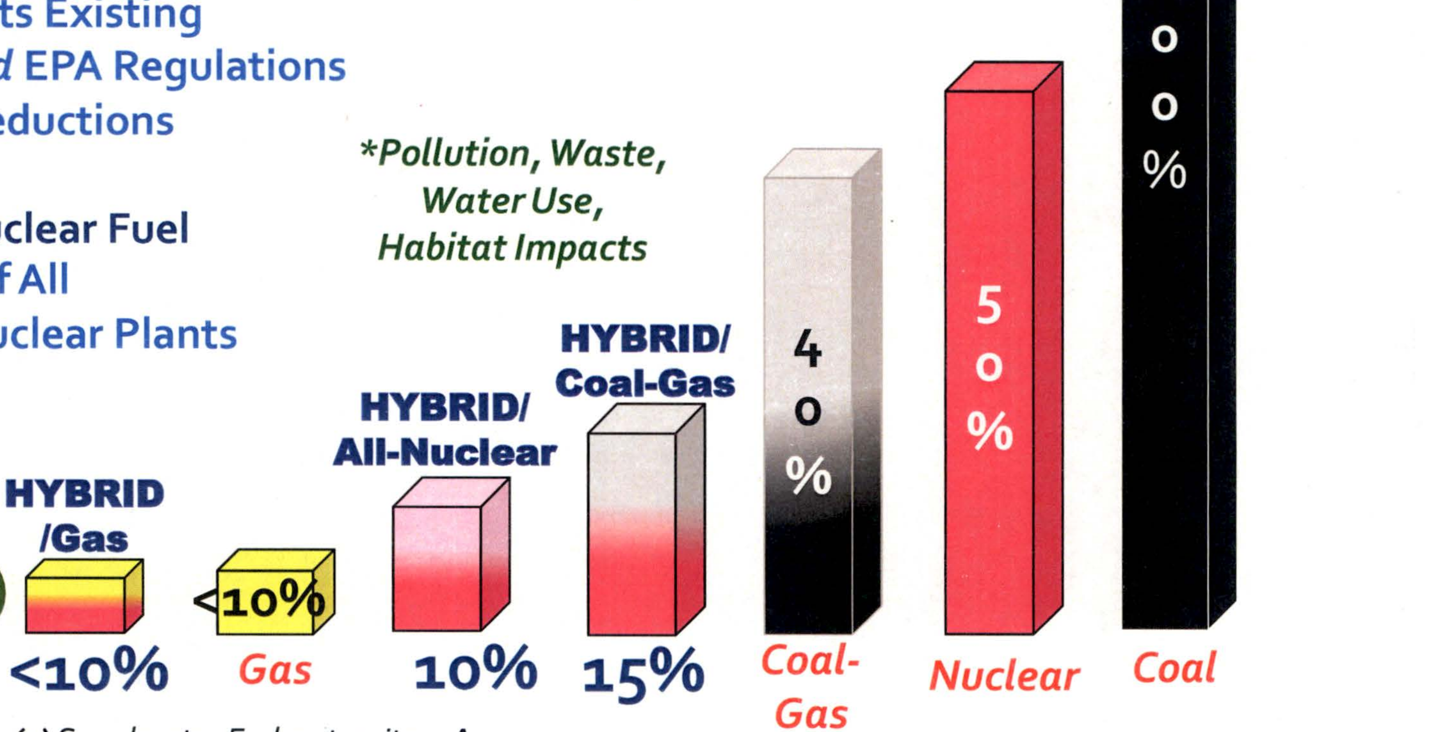
➤ HYBRIDS ECO-FRIENDLY

CONCEPT

ENVIRONMENT: *Summary*
/Biosphere Overview

- **MOST SUSTAINABLE**
  - ✓ Conserves Resources

- **SOLVES MANY PROBLEMS***
  - ✓ Easily Meets Existing & *Proposed* EPA Regulations
  - ✓ Massive Reductions
    - CO_2[1]
    - Spent Nuclear Fuel
  - ✓ Cleanest of All Fossil & Nuclear Plants



Note: *(1) See chapter End-notes, item* ***A****.*

CONCEPT

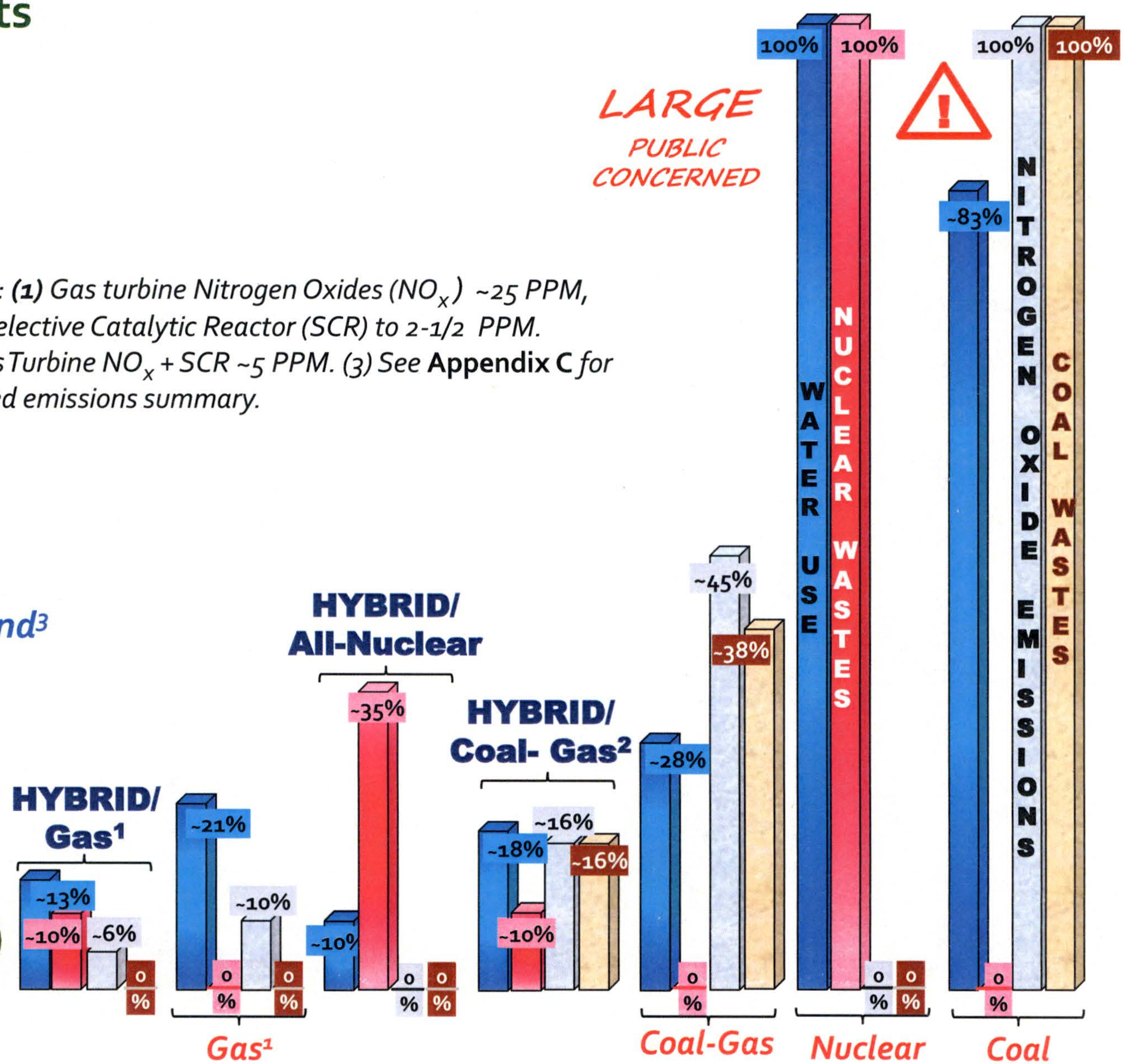
ENVIRONMENT: *Contrasts*

/Biosphere Impacts

Notes: **(1)** *Gas turbine Nitrogen Oxides (NO_x) ~25 PPM, with Selective Catalytic Reactor (SCR) to 2-1/2 PPM.* **(2)** *Gas Turbine NO_x + SCR ~5 PPM. (3) See* **Appendix C** *for detailed emissions summary.*

➢ **PRACTICAL SOLUTION**

✓ *Best All-Around*[3]

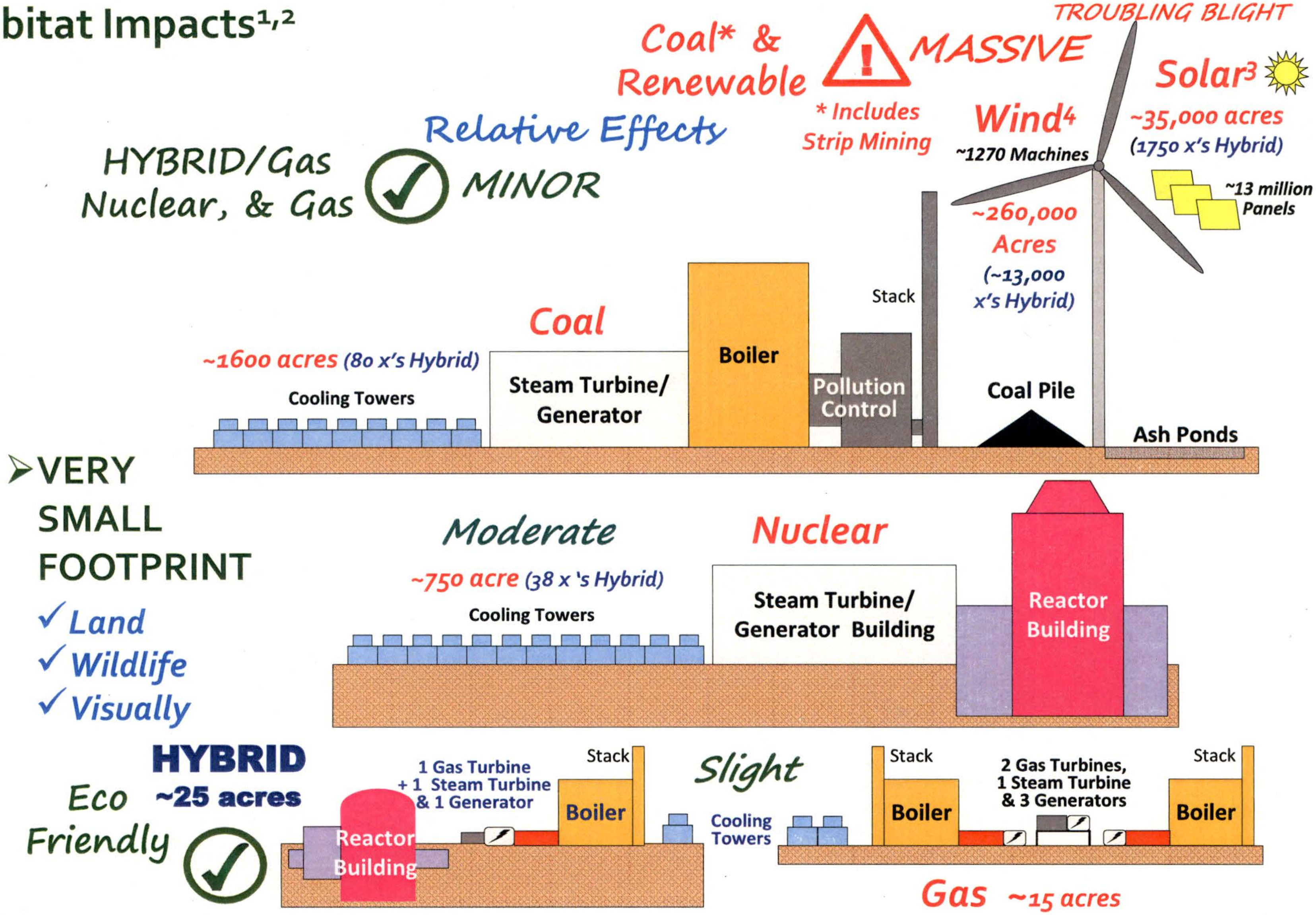


CONCEPT

ENVIRONMENT: *Contrasts*

/Habitat Impacts[1,2]

Hybrid-Nuclear Energy



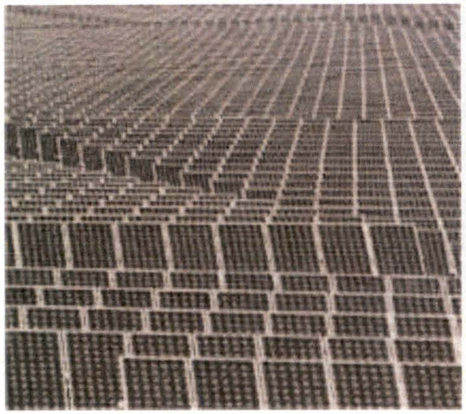
<u>Notes:</u> *(1) Similar output, ~1000 MW electric, 7800 Gigawatt-hours/year. (2) Power plant buildings & structures ~to scale. (3) Western US,* **Ref.** 3. *(4) US Midwest* **Ref** *(4), See chapter End-notes, item* **B.**

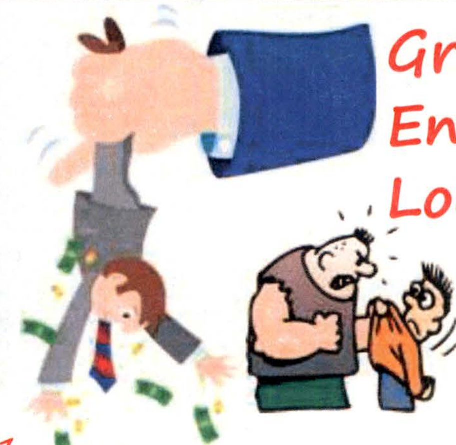
CONCEPT

ENVIRONMENT: *Contrasts*

/Habitat Impacts

The Day they Paved Paradise to Put Up Renewable Energy!





Green Energy Lobby

TO MEET 100% OF US ELECTRIC DEMAND[1], USING RENEWABLE ENERGY, NEED ENTIRE LAND AREA OF:

NEW YORK, PENNSYLVANIA; MASSACHUSETTS; CONNECTICUT; RHODE ISLAND; DELAWARE; MARYLAND; VIRGINIA; NORTH CAROLINA; SOUTH CAROLINA; FLORIDA; GEORGIA

Or use ~12,500 acres for ~500 Hybrid power plants

Notes: *(1) Us electric usage in 2017 about 3820 billion kilowatt-hours,* **Ref. 68.** Renewable land area rough calculation assumes average renewable capacity much less than half of best values of previous page, including mismatch between grid peak needs and actual time-of-day production of renewable energy. Further, access road acreage is not trivial for wind turbines because so many turbines are required.

CONCEPT

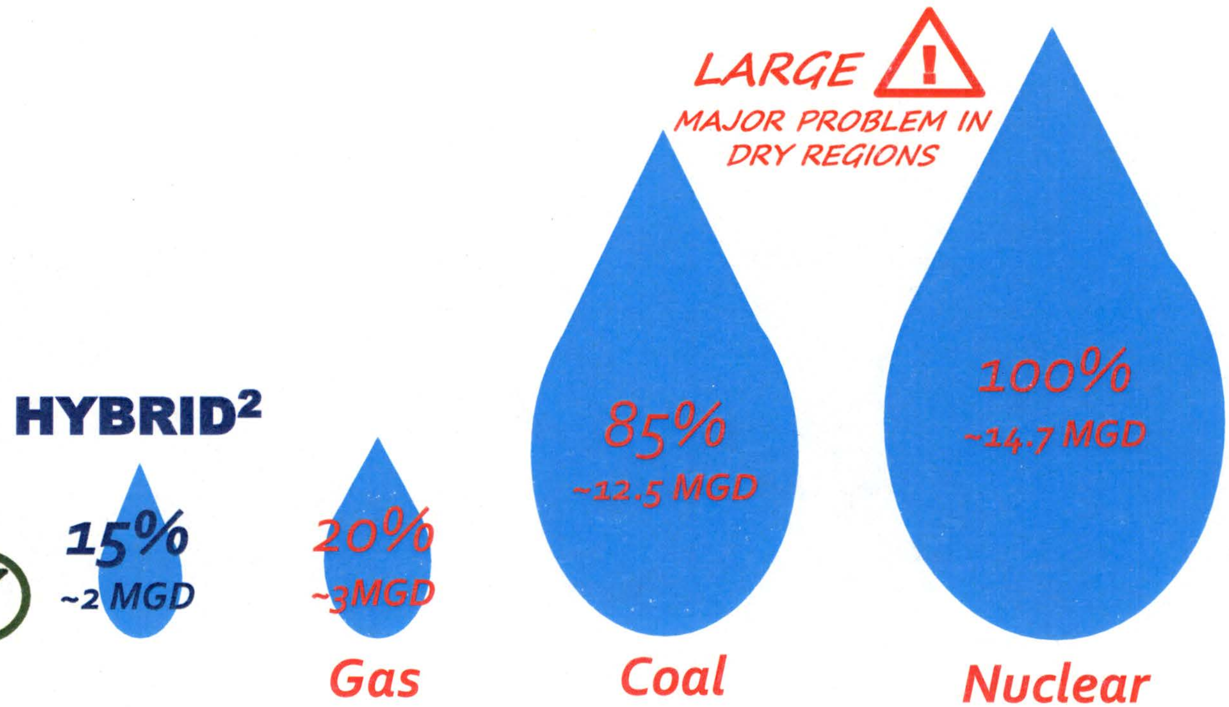
ENVIRONMENT: *Contrasts*

/Water Needs

➢ CONSERVES CRITICAL RESOURCE[1]

✓ *Aquatic Life Minimally Affected*

Eco Friendly ✓



MGD = Million Gallons per Day

Notes: ***(1)*** *All Plants ~1000 MW Output using wet mechanical draft cooling towers* – **Ref. 7**. ***(2)*** *Using "once-thru" cooling (river, lake or ocean water) with Hybrid yields minimal water needs (~0.05 MGD or << 1%) and aquatic impacts. Alternatively, air-cooled condenser (~0.1 MGD or < 1%) could be used with small efficiency and output loss.*

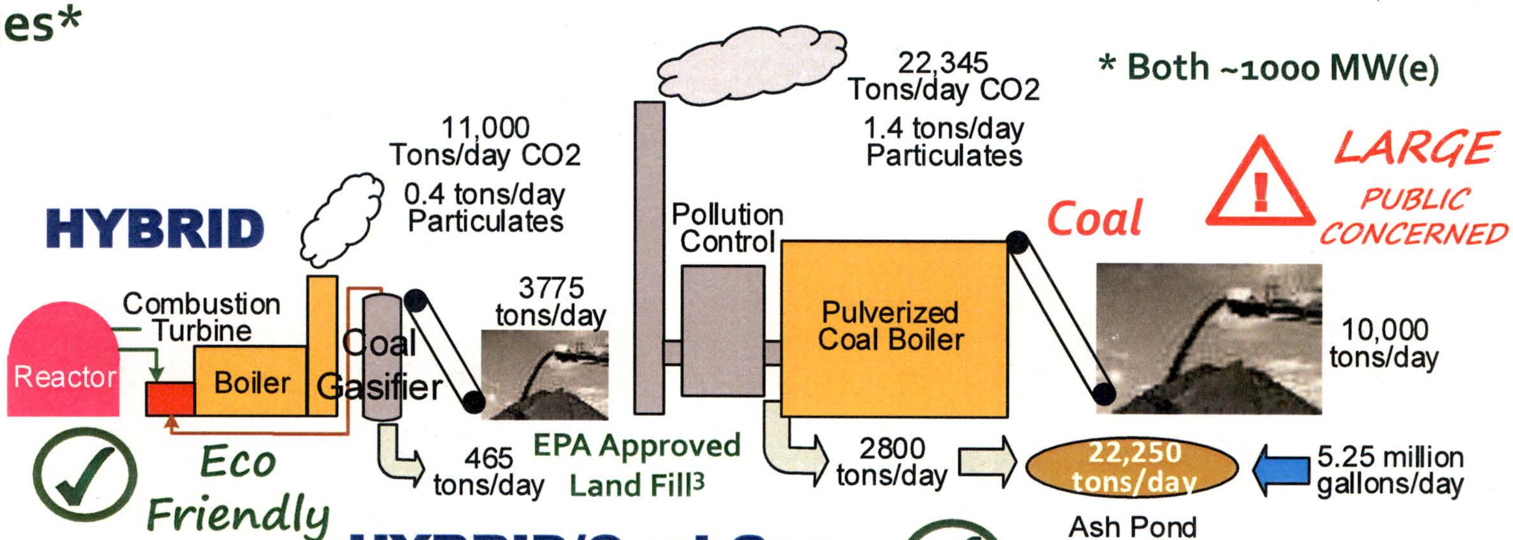
CONCEPT

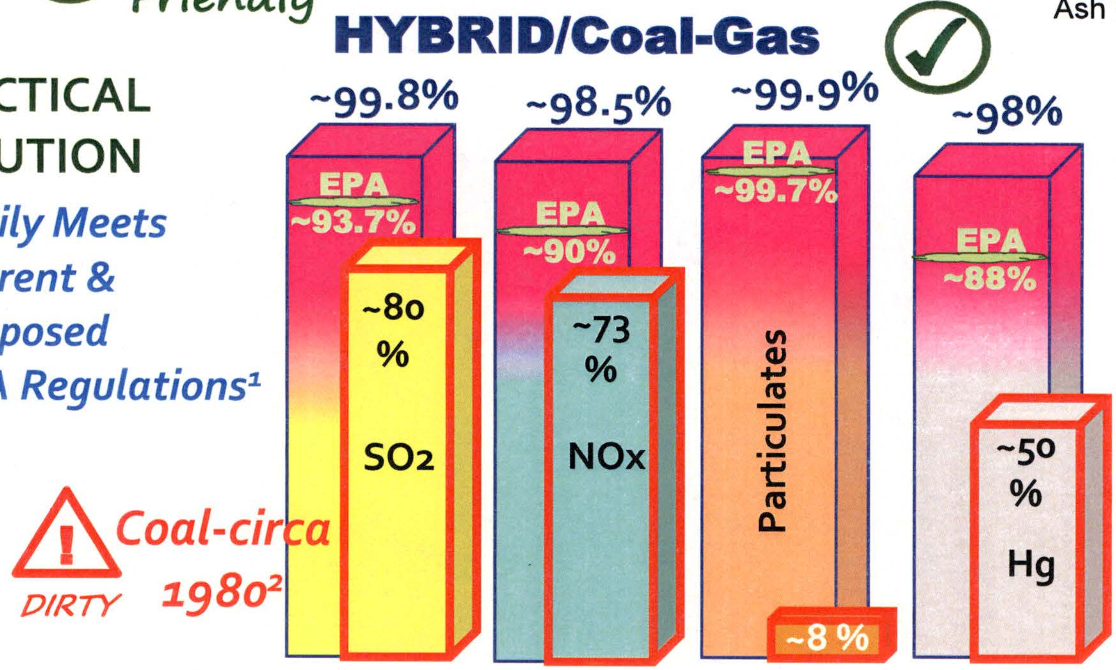
ENVIRONMENT: *Contrasts*

/Discharges*

Hybrid-Nuclear Energy

* Both ~1000 MW(e)





Pollution Reduction

➢ PRACTICAL SOLUTION

✓ *Easily Meets Current & Proposed EPA Regulations*[1]

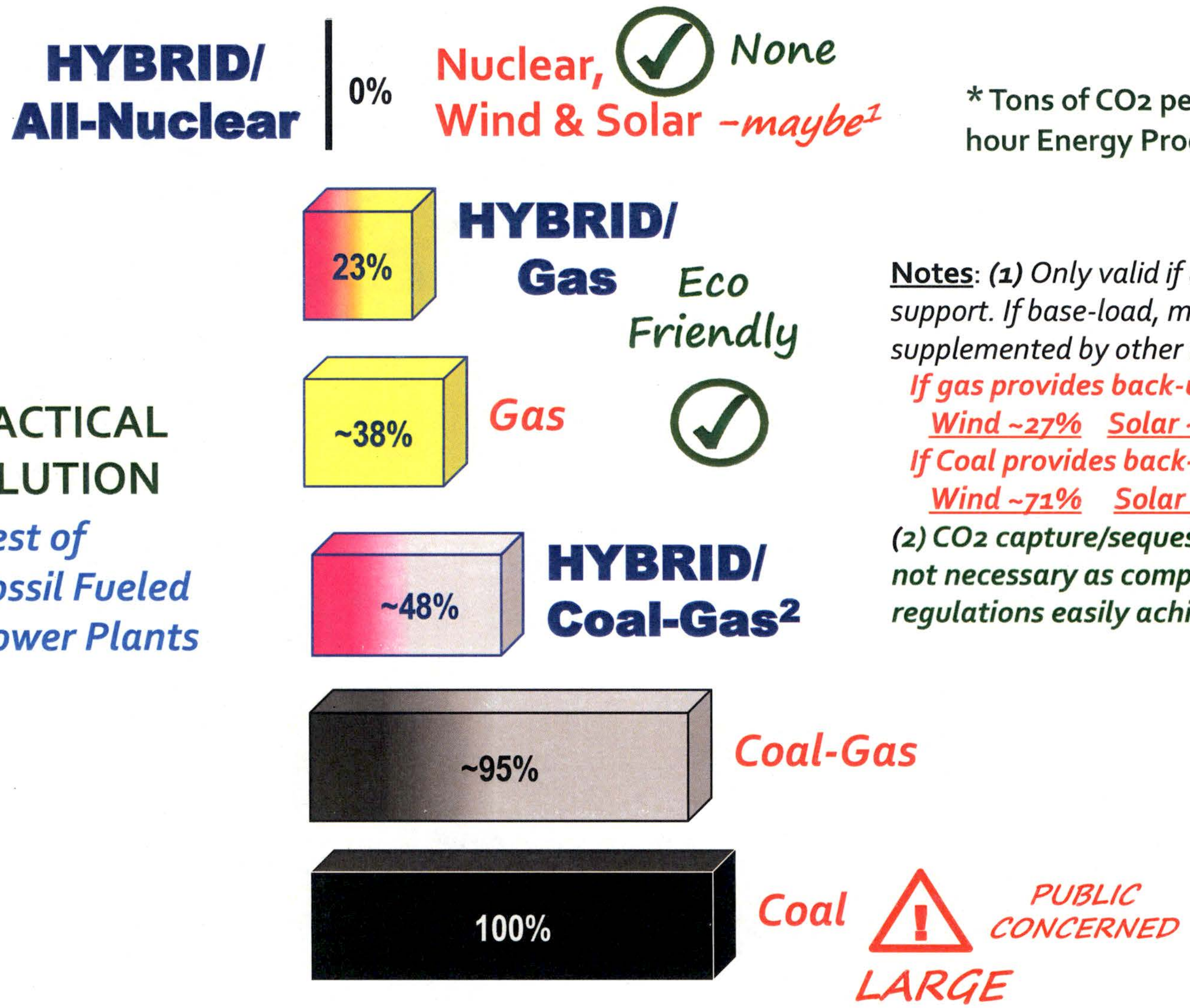
Notes: *(1) EPA Current: New Source Performance Standards with Mercury & Air Toxin Standards. Pending: Cross-State Air Pollution Rule; exact requirements vary but heavily impacts NOx & SO2 - see chapter End-notes, item* ***B.(2)*** *See* **Ref. 12**.
(3) ~ 16,000 cubic feet.

Hg = Mercury
NOx =Nitrogen Oxides
SO2 = Sulfur Dioxide

CONCEPT

ENVIRONMENT: *Contrasts*

/Greenhouse Gas (CO_2)*



* Tons of CO2 per Megawatt-hour Energy Production

➢PRACTICAL SOLUTION

✓*Best of Fossil Fueled Power Plants*

<u>Notes</u>: **(1)** *Only valid if used in peaking support. If base-load, must be supplemented by other types of power.*

If gas provides back-up support:

<u>Wind ~27%</u> <u>Solar ~29%</u>

If Coal provides back-up support:

<u>Wind ~71%</u> <u>Solar ~75%</u>

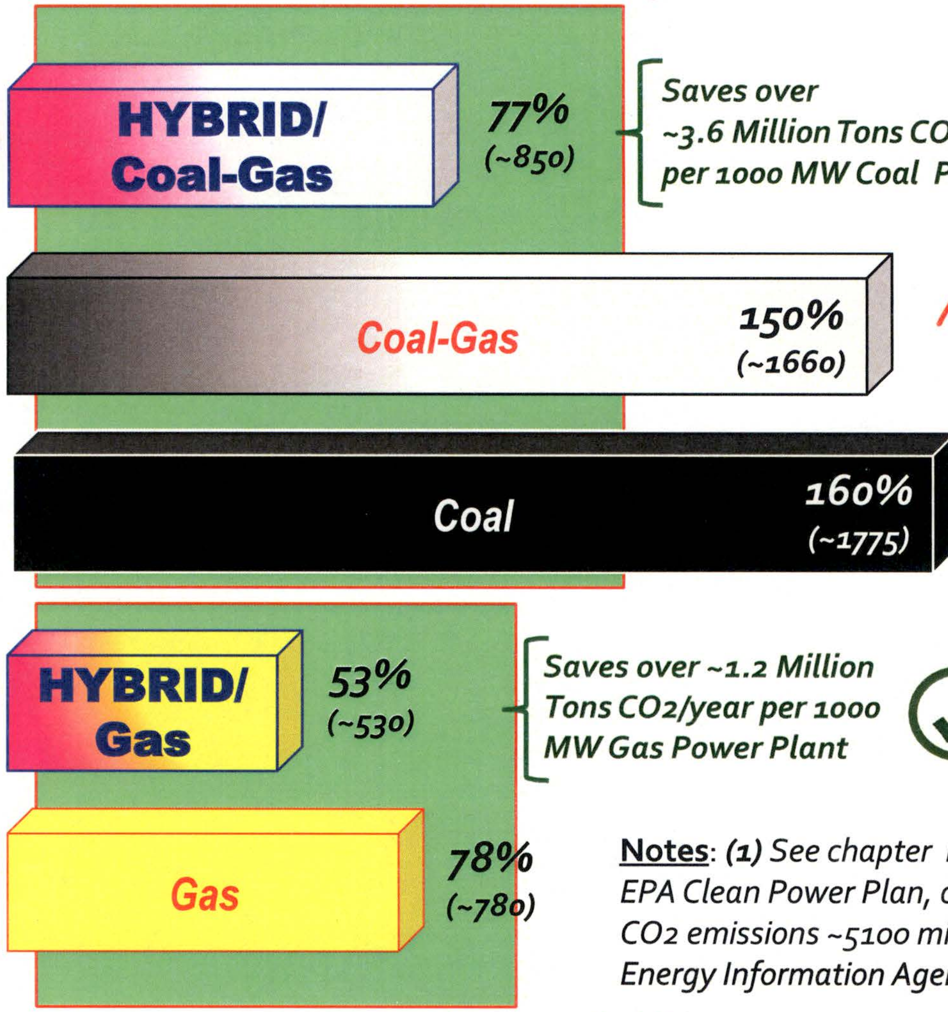
(2) CO2 capture/sequestration not necessary as compliance with regulations easily achieved.

CONCEPT

ENVIRONMENT: *Contrasts*

/Greenhouse Gas[1]

Coal Plant EPA Limit[2]
~1100 Pounds per Megawatt-hour (net)



Small ✓

Saves over ~3.6 Million Tons CO2 /Year per 1000 MW Coal Power Plant

MASSIVE ⚠

- ➢ PRACTICAL SOLUTION
  - ✓ *Easily Meets EPA Reduction Targets[2]*
- ➢ ~15% REDUCTION, TOTAL US CO_2 ~770 million tonnes[3]
  - ✓ *Replace Existing Coal & Gas with HYBRIDS*

Saves over ~1.2 Million Tons CO2/year per 1000 MW Gas Power Plant

✓ Eco Friendly

Notes: ***(1)*** *See chapter End-notes item* ***A***.***(2)*** *EPA Clean Power Plan, circa 2016.* ***(3) 2017*** *US CO2 emissions ~5100 million metric tons per US Energy Information Agency's website –* **Ref. 10**.

Gas Plant EPA Limit[2]
~1000 Pounds per Megawatt-hour (net)

CONCEPT

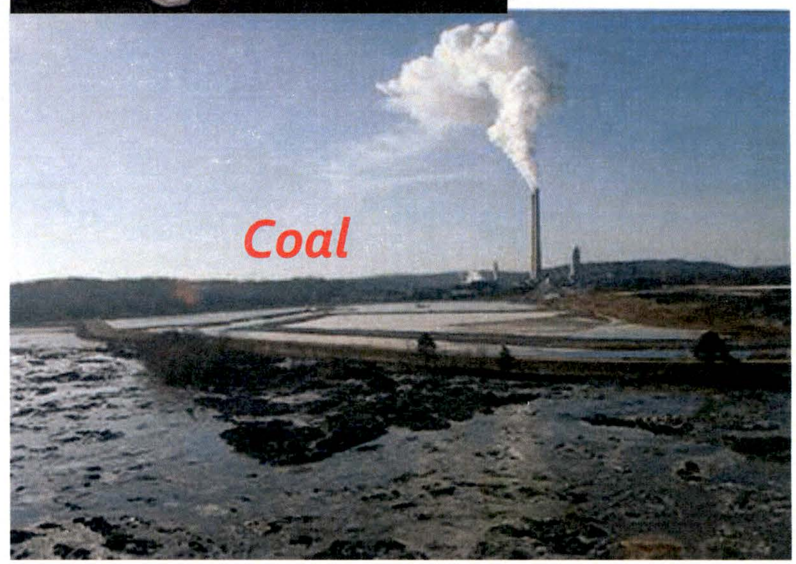
ENVIRONMENT: *Contrasts*

/Coal Wastes

HYBRID

MASSIVE

PUBLIC CONCERNED



➢ PRACTCAL SOLUTION

- ✓ *Glass-like Slag*[1]
  - *Does not Leech into Environment*
- ✓ *+99% Reduction*
- ✓ Sludge Ponds Eliminated

Eco Friendly ✓

Note: ***(1)*** *Vitreous slag saleable byproduct of coal gasification process, useful as aggregate for construction industry and abrasive grit . Sulfur also useful salable byproduct used in chemical industry.*

CONCEPT

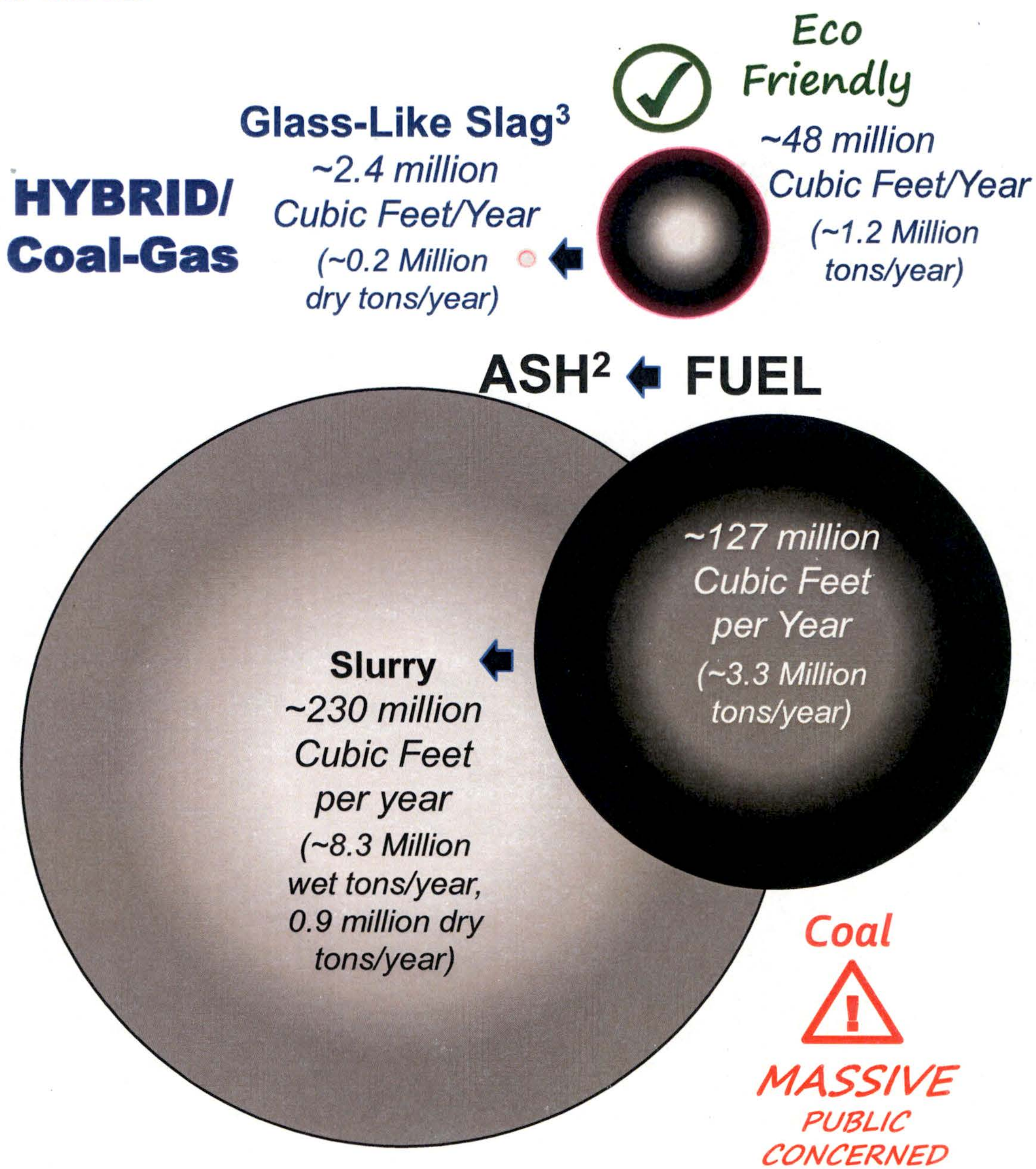
ENVIRONMENT: *Contrasts*

/Coal & Waste[1]

Hybrid-Nuclear Energy

- **LARGE REDUCTION**
  - ✓ *~65% Less Coal*
  - ✓ *~80% Less Ash Waste*
- **GREATLY REDUCED IMPACTS**
  - ✓ *Mining*
  - ✓ *Transport*
  - ✓ *Disposal*

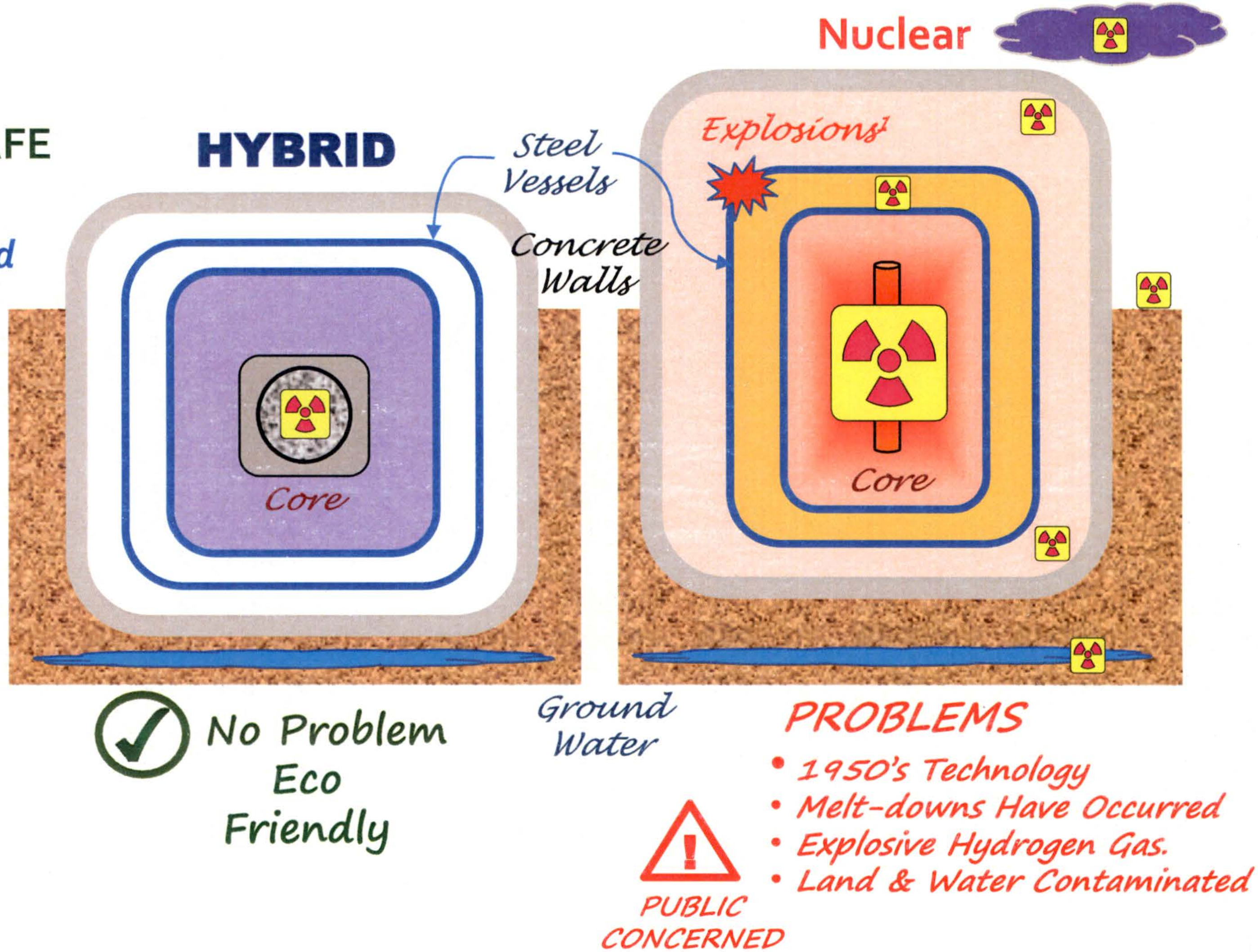
*<u>Notes:</u> **(1)** Similarly sized large power plants using US Midwest coal. **(2)** By US EPA regulations, not hazardous material, but sheer volume & leachability creates numerous problems. **(3)** Not prone to leeching.*



CONCEPT

ENVIRONMENT: *Contrasts*
/Radiation Releases

- PUBLIC ALWAYS SAFE
  - ✓ *Avoids Water Cooled Reactor Problems*



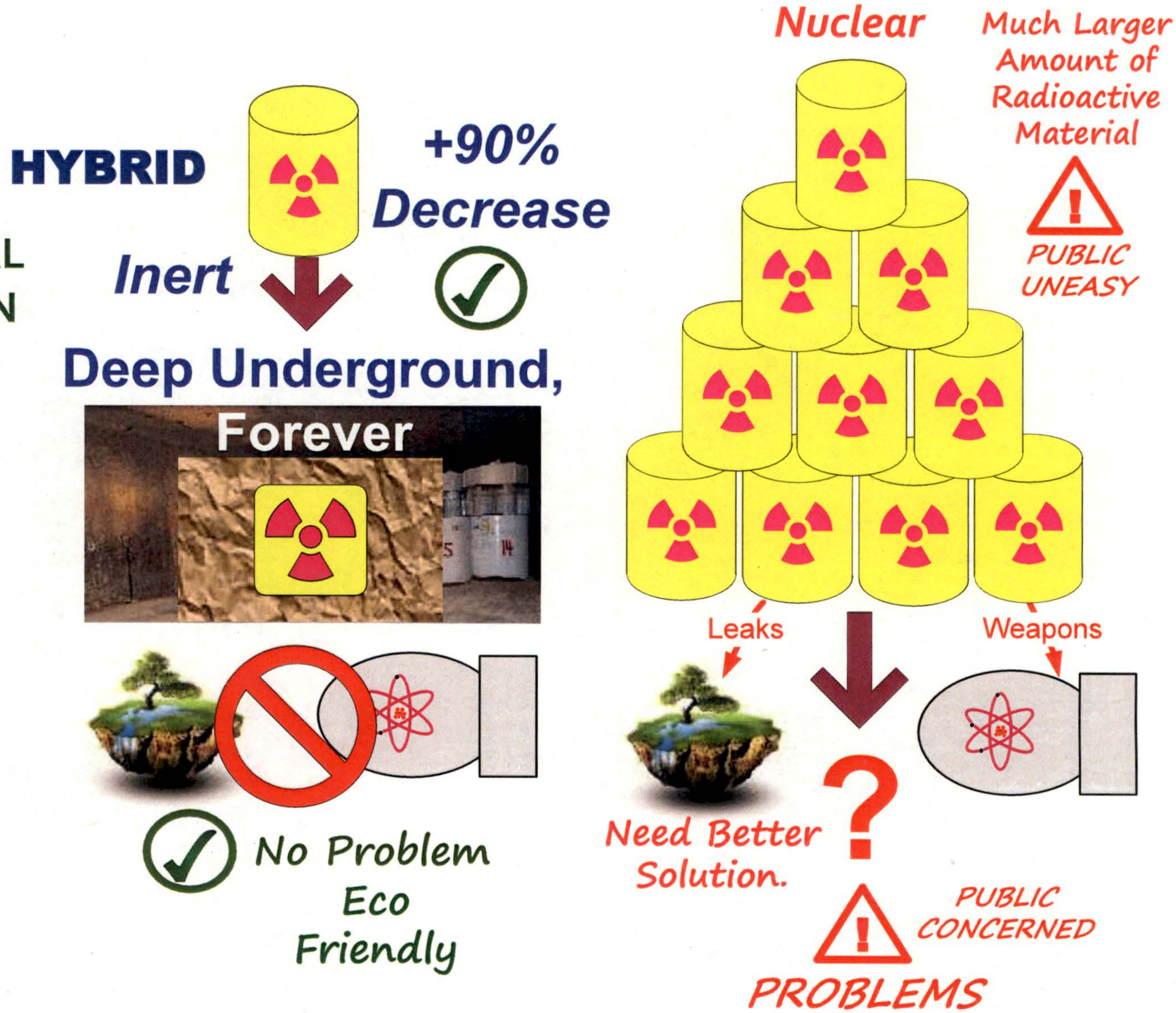
CONCEPT

Notes: *(1) Hydrogen gas formed when high-temperature water reacts with fuel's zirconium alloy tubing.*

ENVIRONMENT: *Contrasts*

/Spent Nuclear Fuel

- PRACTICAL SOLUTION

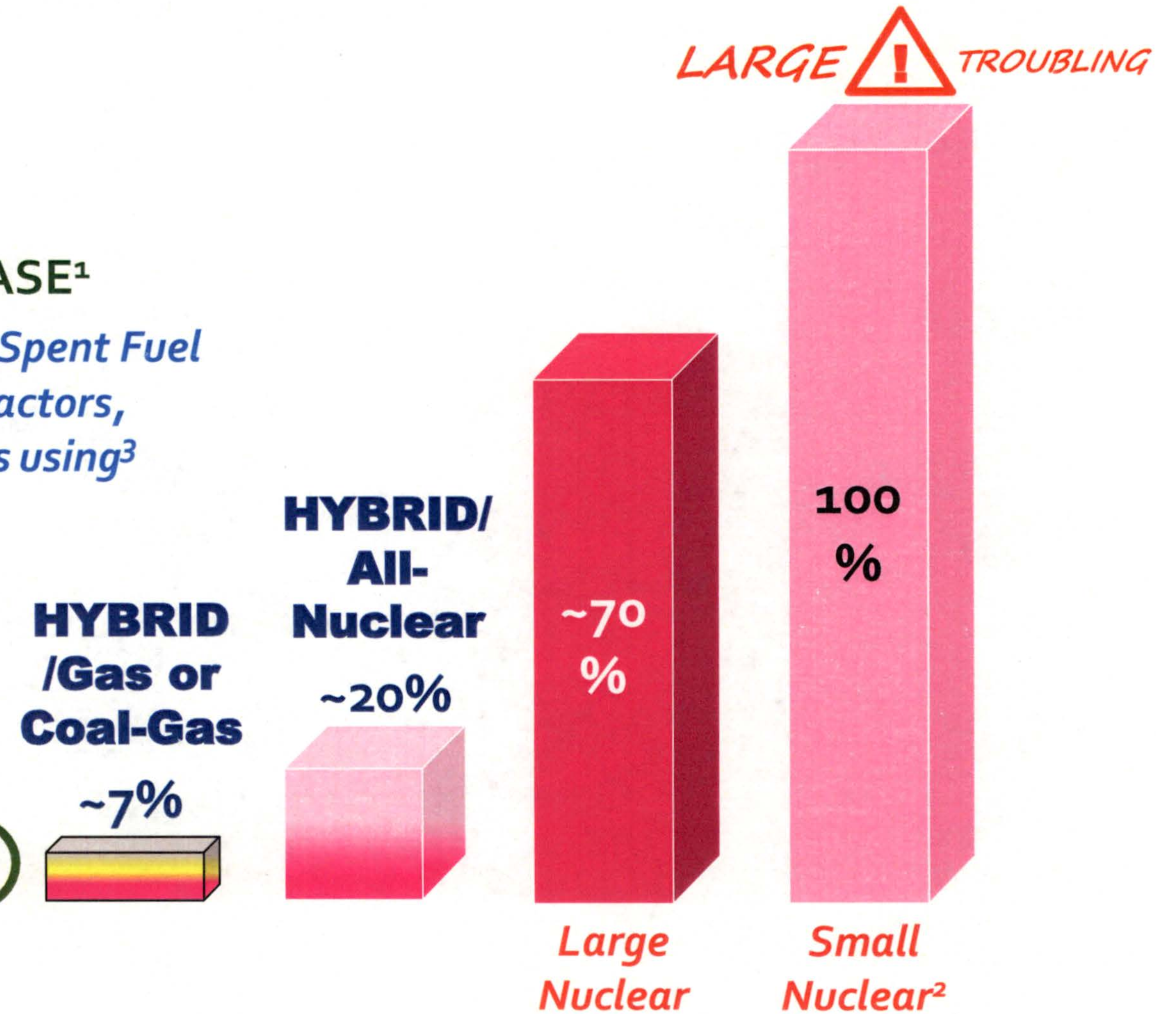


CONCEPT

ENVIRONMENT: *Contrasts*
/Spent Nuclear Fuel

- **MASSIVE DECREASE[1]**
  - ✓ *<u>Significantly</u> Less Spent Fuel Than All Other Reactors, including Breeders using[3]*
    - *Liquid Fuels*
    - *Molten Salt*

Eco Friendly ✓



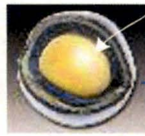
<u>Notes:</u> *(1) Per MWh Electric Production, see* **Technical: *Contrast*/Nuclear Fuel**. *(2) Small Modular Reactor - SMR (3) These types of reactors can produce more fuel than they consume, provided the fuel is reprocessed.*

CONCEPT

ENVIRONMENT: *Contrasts*
/Spent Nuclear Fuel

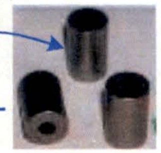
HYBRID

➢ PROBLEM SOLVED
- ✓ *Fuel not Prone to Reacting with Environment*
- ✓ *Plutonium Cannot be Extracted*



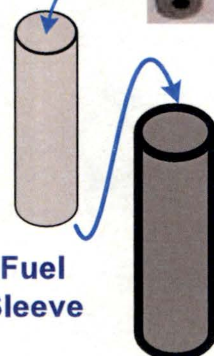
Fuel Kernel

Fuel Particle



Fuel Pellets

Intact in reactor. ✓

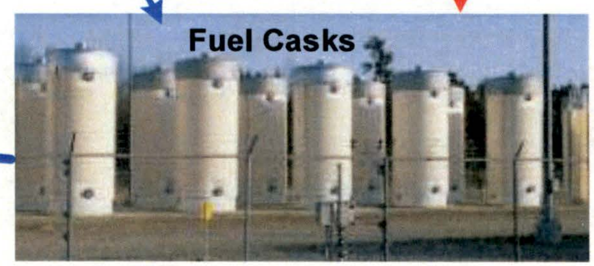


Fuel Sleeve

Boron Carbide Shipping Sleeve

Fuel coatings and B_4C shipping sleeves essentially inert. ✓

Loaded into Casks



Multiple Barriers ✓

SAFE ✓

Deep Underground Entombment.

Nuclear

Fuel Assembly

Fuel Rod

Fuel Pellet

⚠ *Pellet Heavily degraded in reactor. Spent fuel rods will leak and react with environment unless sealed in cask. Lifetime of cask limited.*

⚠ *Limited Barriers*

Underground ?

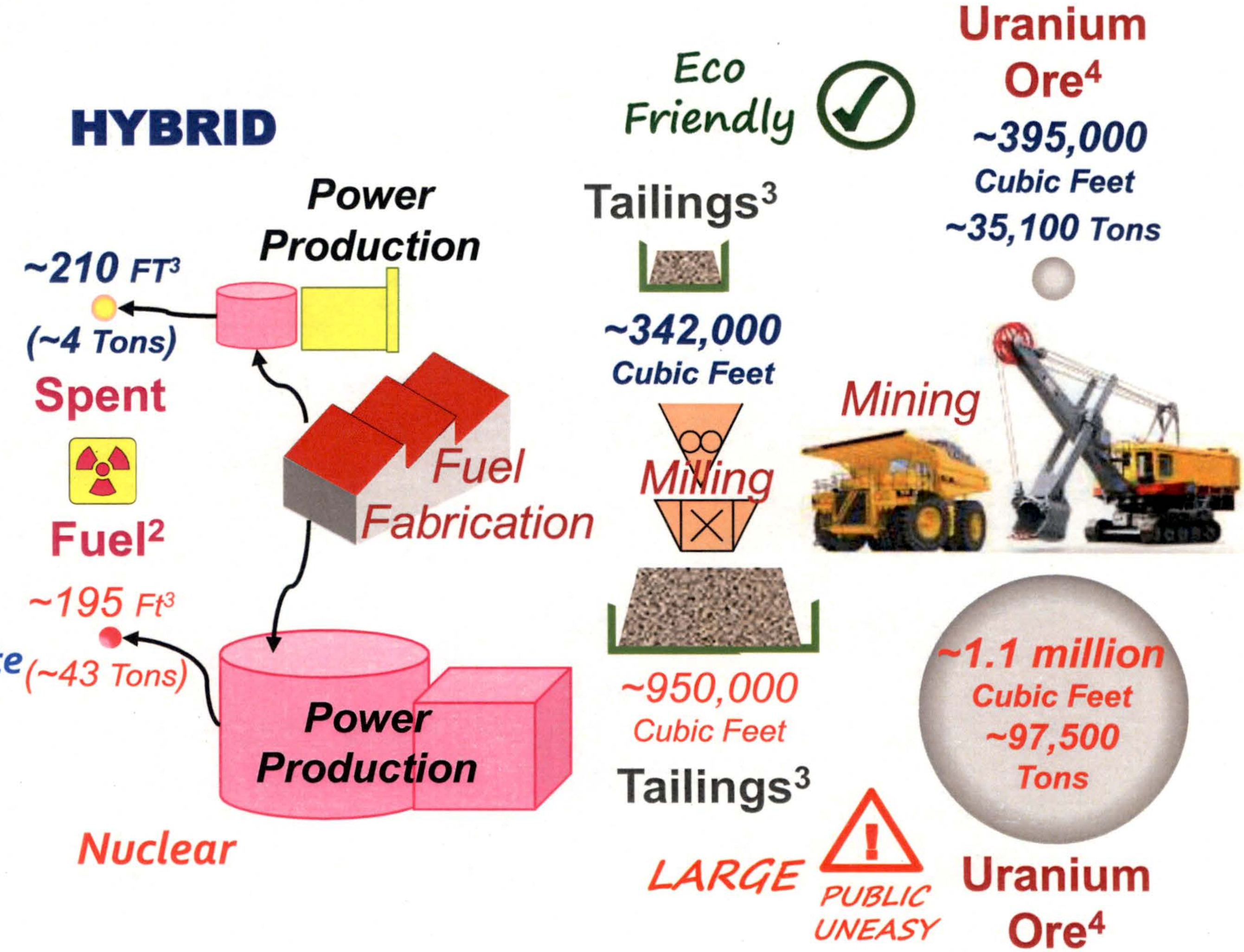
⚠ *PUBLIC UNEASY*

CONCEPT

ENVIRONMENT: *Contrasts*

/Uranium Needs[1]

- ➢ LARGE ORE REDUCTION
  - ✓ ~65%
- ➢ GREATLY REDUCED IMPACTS
  - ✓ *Mining*
  - ✓ *Transport*
  - ✓ *Tailings/Waste*



<u>Notes:</u> ***(1)*** *Similarly sized large (~1000 MWe) plants, 1 year operation.* ***(2)*** *Dangerous if not properly contained. Based on volume of fuel assembly or sleeve (hybrid) containing used fuel.* ***(3)*** *Based on* **Ref. 13**. ***(4)*** *Per World Nuclear Association, 1 tonne natural Uranium yields ~44 million kilowatts electricity, ore ~0.2 % Uranium. Conventional enrichment ~4.95%, Hybrid ~12%, but much less uranium needed to produce electrical energy*

CONCEPT

ENVIRONMENT: *Contrasts* /Sustainability

	HYBRID	*Gas*	*Coal*	*Nuclear*	*Wind & Solar[1]*
Fuel Abundance	GOOD	*Limited*	*Modest*	*Limited*	*Unlimited*
Practical Availability	VERY GOOD	*Good*	*Good*	*Good*	*Poor*
Energy Utilization	VERY GOOD	*Good*	*Fair*	*Fair*	*Poor*
Realistic Potential	VERY GOOD	*Good*	*Poor*	*Average*	*Marginal*
➢HYBRID SUPERIOR — Net[2]	★-	✓+	✗+	✗+	✗+

★ = *good,* ✓ = *average,* ✗ = *needs work. See* ***Appendix A*** *for ranking method*

<u>**Notes**</u>: ***(1)*** *Solar only erratically available during day (in limited and varying amounts) due to position of sun, clouds, season. Wind highly susceptible to presence and velocity of breeze which significantly affects turbine efficiency. Both wind & solar are highly location sensitive which is generally not the case for other resources which can also be placed near load centers, thereby reducing transmission costs.* ***(2)*** *Average of categories.*

CONCEPT

ENVIRONMENT: *Rankings*
/Nuclear Plants

Category[1]	HYBRID	*Gas Reactors*	*Water Reactors*
Solid Waste[2]	★	✗+	✗
Water Use	★	✗+	✗
Land Use	★	✓+	✗
Habitat Impact[3]	★	✓-	✗
Air Pollution	✗	★	★
CO_2 Emissions	✗	★	★
Sustainability	★	✗	✗
NET[4]	✓+	✓-	✗+

★ = *Best*, ✓ = *Average*, ✗ = *Needs Work.*

➢ HYBRID BEST

✓ *Minimum Impacts*

Notes: *(1) Scoring relative to each other.* ***(2)*** *Volume, inertness, radiation hazard.* ***(3)*** *Average of land & water use.* ***(4)*** *Average of categories.*

CONCEPT

ENVIRONMENT: *Rankings*

/Power Plants

CATEGORY[1]	HYBRID	Gas	Wind & Solar[4]	Nuclear	Coal
Solid Waste[2]	★-	★-	★	✗+	✗
Water Use	✓+	✓+	★	✗	✗
Land Use	★	★	✗	★-	★-
Habitat Impact[3]	★	✓+	✗	✗	✗
Air Pollution	★-	✓	★-	★	✗
CO_2 Emissions	✓+	✓+	✓+	★	✗
Visual Pollution	★	★-	✗	✓	✓-
Sustainability	★	✓-	✗	✗+	✗+
NET[5]	★-	✓+	✓-	✓-	✗+

★ = *Best*, ✓ = *Average*, ✗ = *Needs Work.*

➤ **HYBRID MOST ECO FRIENDLY**

✓ ***Safeguards Earth's Resources***

Notes: *(1) Scoring relative to each other. (2) Tons from fuel: chemical & radiation hazards. Gas includes sulfur (H_2S) removed at process plant. (3) Average of land & water use. (4) Solids, air pollution, CO_2 emissions weighted to achieve 90% capacity factor using gas power plant. (5) Average of Categories.*

CONCEPT

ENVIRONMENT: *End-notes*

***A. <u>Greenhouse Gas.</u>** The environmental impacts of the various energy related emissions, discharges and resource uses are relatively straightforward to evaluate and overcome, with one glaring exception. The future influences of man's CO_2 emissions are unknown, complicating the need for mitigation efforts.*

In the 1990's, the supposed distant impacts of man-made CO_2 emissions were characterized as "Catastrophic-Global-Warming". In the early 2000's, the fears were downgraded to "Global-Warming", while by around 2010 the perceived threat degenerated into "Climate-Change".

The actual concern stems primarily from various computer models attempting to forecast long-range planetary conditions. These models are exceptionally complicated collections of non-linear, initial-value partial differential equations containing vast armadas of variables that may or may not be realistic. Also, the key elements that satisfactorily characterize the chaotic nature of the planet's climate may or may not be present, particularly when considering lengthy temporal (time) and vast spatial (planet's enormous atmosphere) considerations.

Ordinarily, complex computer simulations are tested against reality to confirm model validity (uniqueness and usefulness in mathematical parlances). However, non-linear climate models are so complicated and shrouded in the fog of uncertainty that there is no way to physically confirm whether or not meaningful solutions to the models are even possible. Simply stated, the impacts (if any) of CO_2 on the distant future's climate cannot be determined from the existing computer models/simulations. The models are not fit for the intended application. Assertions of a temperature rise of "X" in the distant future are nonsense.

The issue is further convoluted by assuming a priori that climate change must be disastrous for mankind. Maybe not. The earth has been warming since the last Ice Age. Also, CO2 is vital for survival of life on the planet. See **REF. 64** *for further discussions on the various considerations associated with CO2 and the environment.*

Forecasts of far-off dire planetary impacts caused by CO_2 emissions are more akin to prophesy, as opposed to pragmatic engineering deductions. However, as discussed at the end of the **Conclusions** *chapter, the entire CO2 dilemma is rather easily resolved from the Hybrid's perspective.*

B. <u>Wind Turbines.</u>** Based on 2.5 MW machine located in US Midwest, capacity factor 28% - see* **Ref. 4** & **FINANCIAL*: End-notes *item* **C**. *Nominal rotor diameter of 400 feet -* **Ref 57**. *Turbine spacing typically 7 to 15 rotor diameters –* **Ref. 56**. *Using average spacing, each machine requires about 205 acres for proper & efficient operation.*

FINANCIAL

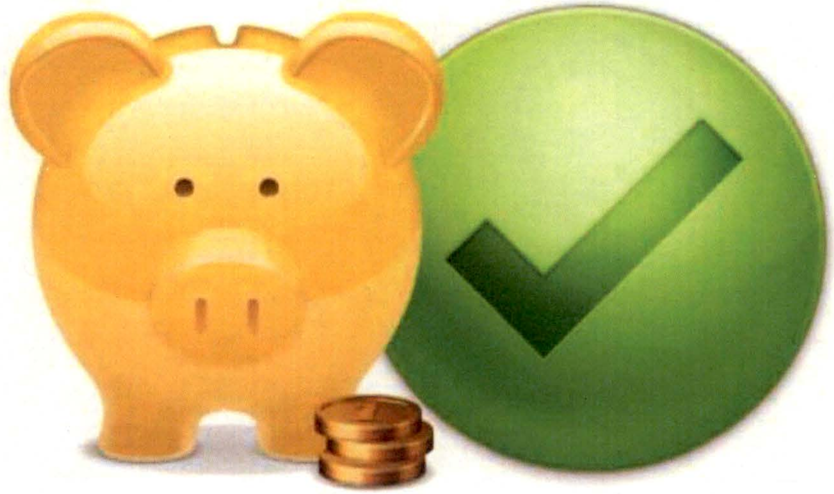
<u>*Historical Perspective*</u>

Providing reasonably priced energy is key to improving the lot of mankind. However, the planet's burgeoning population greatly exacerbates our ability to achieve this objective.

There are numerous ways to provide energy but some are clearly more cost effective than others. Determining the best method is a difficult financial problem. However, the profit motive has always been a very powerful force for efficiently solving complex problems, although such an approach does not guarantee that all investments will succeed.

Profitably building and operating power plants can be a daunting undertaking fraught with financial peril, as numerous utilities (and their customers) can attest. The industry is littered with legions of bankruptcies and forced asset sales that can be fundamentally subscribe to: (1) the lack of a Owner led, strong, knowledgeable, and integrated management team; (2) lack of a common project completion schedule; and (3) lack of sense of ownership and pride by those executing the work . While nuclear plants are certainly very complex undertakings, failure is not confined to these projects alone, as a number of fossil power plant and refinery industry projects (both large and small) have learned to their sorrow.

FINANCIAL: *Summary*



- PROFITABLE
- AFFORDABLE ENERGY

CONCEPT

FINANCIAL: *Revenue* /Sources

Load Following

Base Load

Stabilize Grid[1]

Isotope Production

Chemicals

Plutonium Phase-out

Energy Storage

- **MULTIPLE INCOME STREAMS**
- **EASILY MEETS RECENTLY SIGNED US LAW INTEGRATION of NUCLEAR into NON-ELECTRIC APPLICATIONS[2]**

<u>Note</u>: *(1) Rapid load following & grid reactive load support.* ***(2)*** *Nuclear Energy Innovation Capabilities Act of 2018, US Public Law 115-248*

$ CONCEPT

FINANCIAL: *Characteristics*

- **IN-DEPTH COMPETITIVE ENERGY**
  - ✓ *Exceptionally Fuel Efficient*
    - Both Nuclear & Fossil
  - ✓ *Low-cost Nuclear Fuel*
  - ✓ *Low Build Cost of Combined-Cycle Plant*
- **WHOLE-BETTER-THAN-PARTS[1]**
  - ✓ *Superior Economics Relative to Standalone Reactor + Gas Turbine.*
- **TIME PROVEN ECONOMIES-of-SCALE[2]**
  - ✓ Beats Competition, Much Better:
    - More Efficient
    - More Powerful
    - More Cost Effective

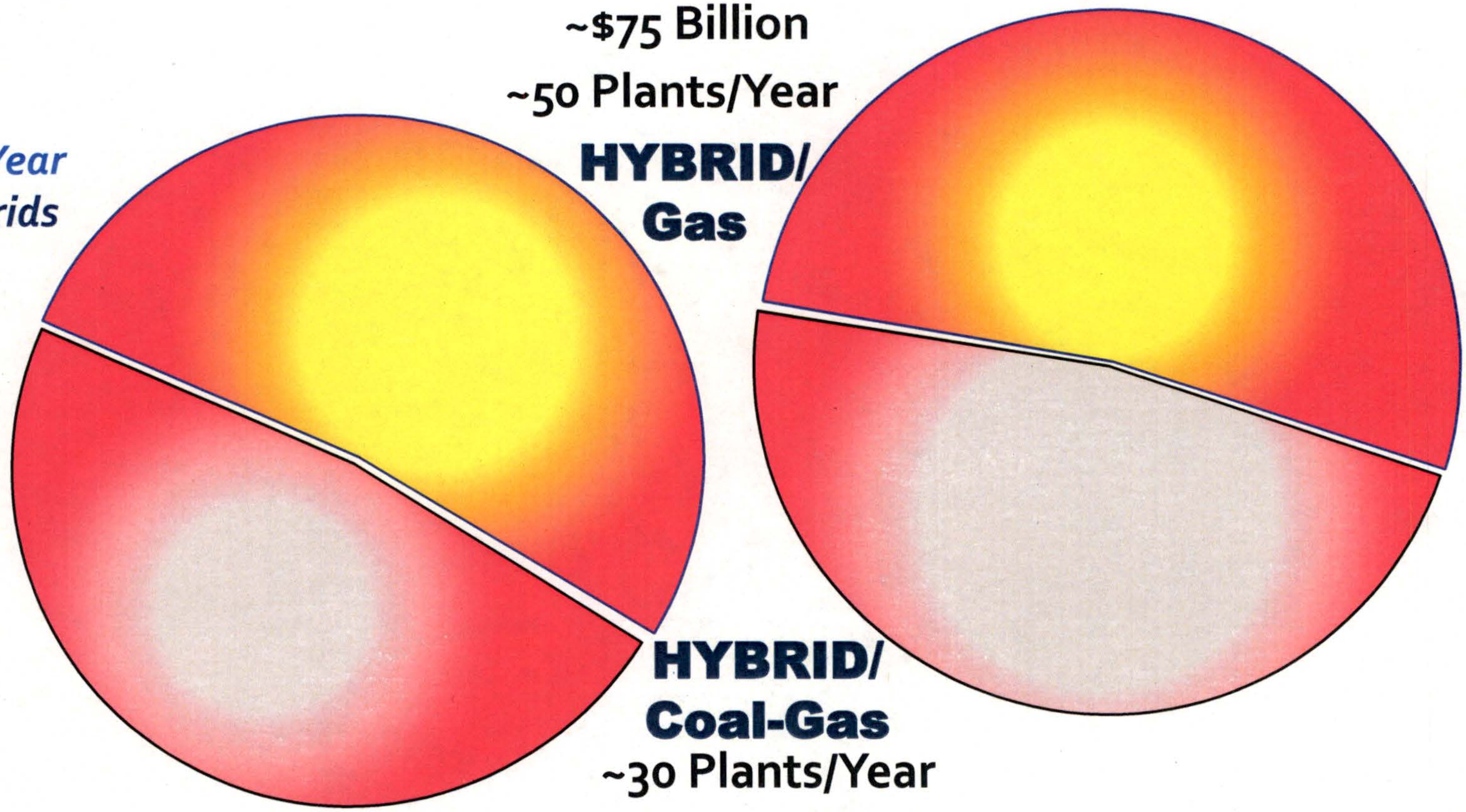
<u>Note</u>: *(1) See chapter End-notes, item **G.** (2) Reliance on mass-production to significantly reduce costs is not a feature of complex power production systems, although standardization is helpful. However, unit costs become smaller as machines become larger, as discussed further in item **H** of* **Financial** *chapter End-notes.*

CONCEPT

FINANCIAL: *Sales Potential*

/World-wide - *New Power Plants*

- VAST[1]
  - ✓ *~$145 Billion/Year*
    ~80 Hybrids /Year



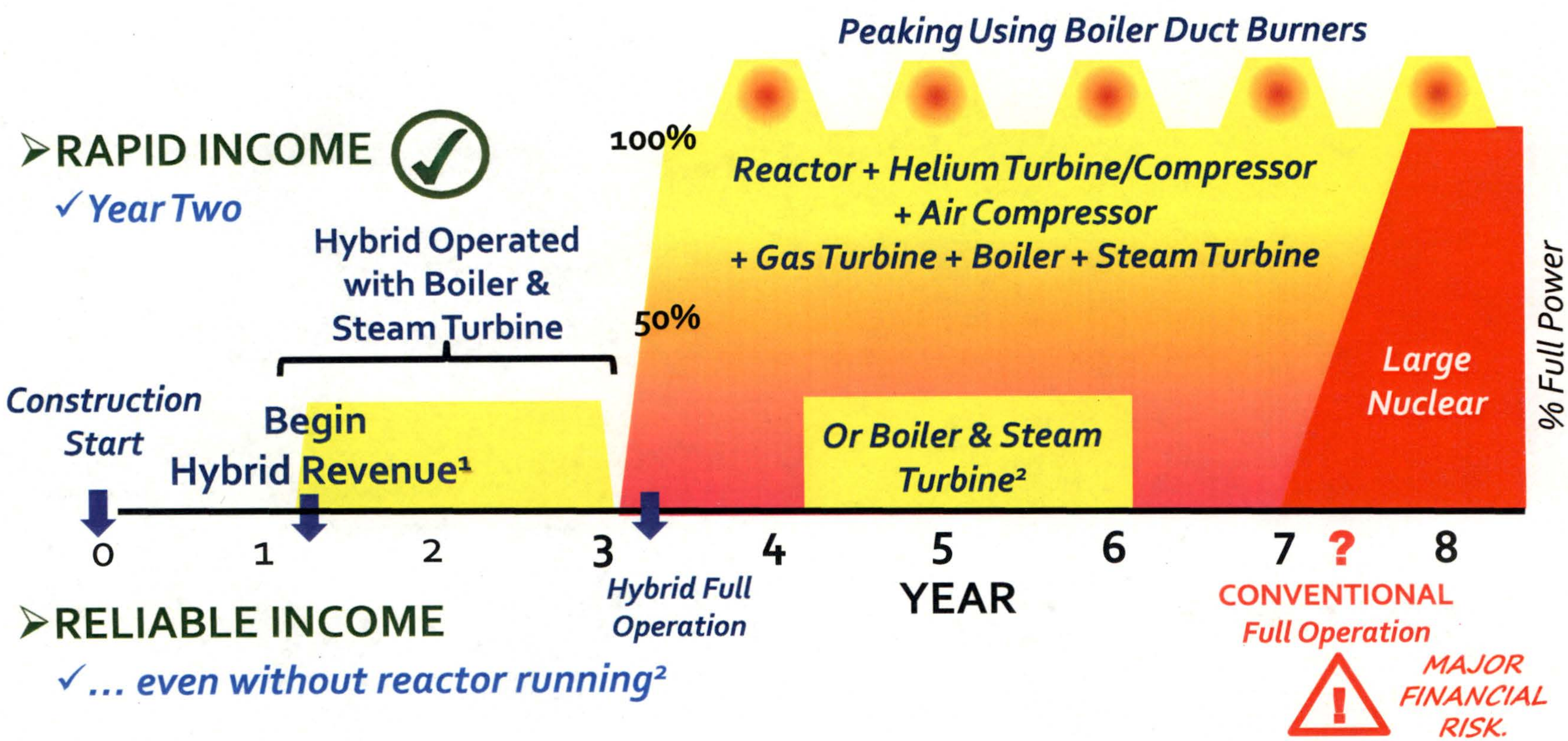
Notes: ***(1)*** *Forecasts based on expected yearly needs and sales for large coal plants and large gas turbines for years 2015 to 2025,* **Refs. 5, 6,** & **17**. ***(2)*** *Gas & Helium turbines*

CONCEPT

FINANCIAL: *Revenue Maximization*

➢RAPID INCOME ✓

✓ *Year Two*



➢RELIABLE INCOME

✓ *... even without reactor running[2]*

Notes: *(1) Reactor completion & testing can occur independently of boiler & steam turbine operation.*
(2) Configuration allows for power production with gas turbine and reactor off-line, see **TECHNICAL: *Thermal Cycle/* High Availability**.

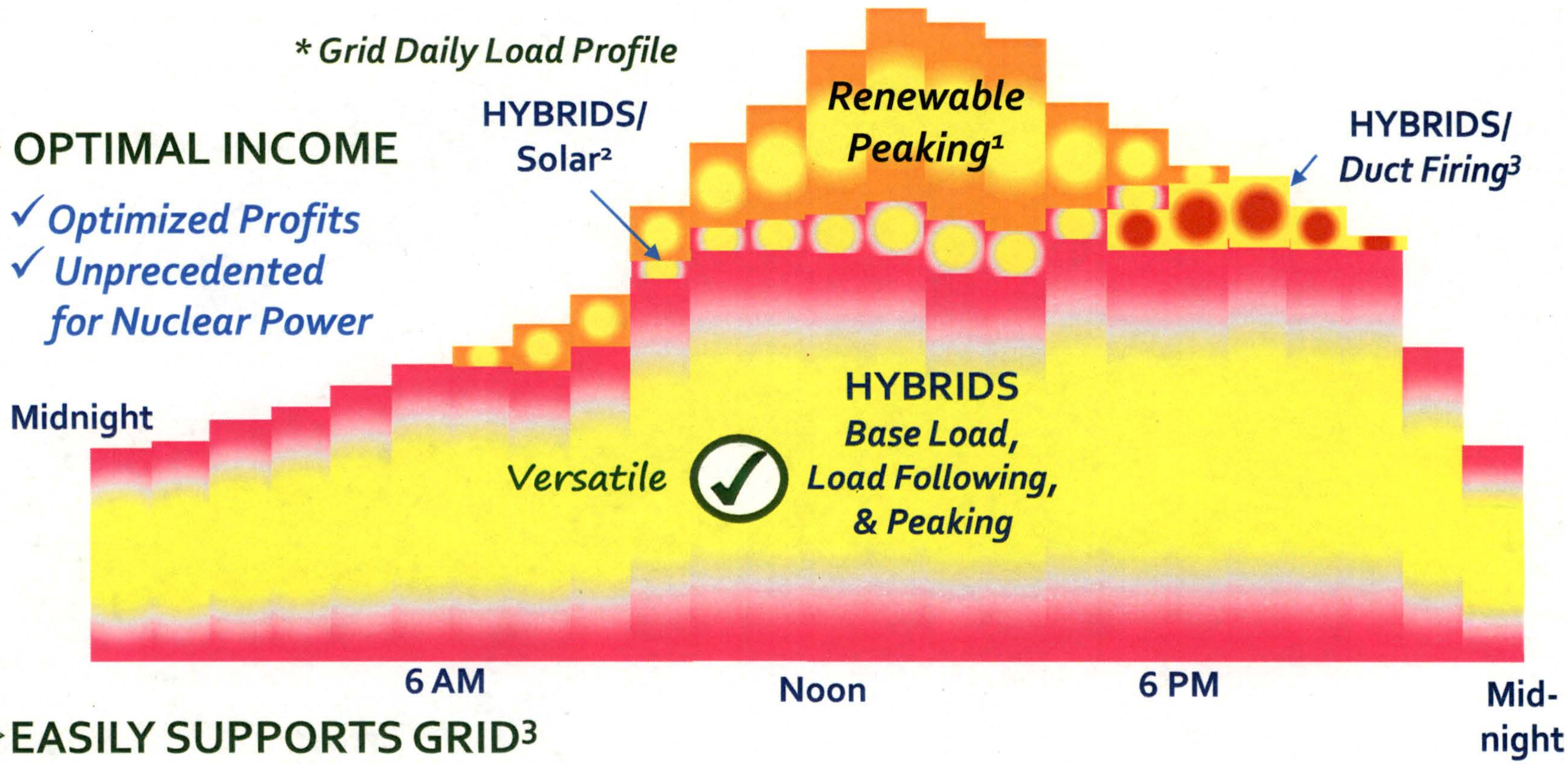
CONCEPT

FINANCIAL: *Market Timing* /Flexibility*

➢ OPTIMAL INCOME

✓ *Optimized Profits*

✓ *Unprecedented for Nuclear Power*



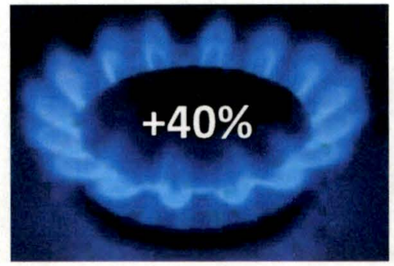
➢ EASILY SUPPORTS GRID³

✓ Unfazed by Variable Renewables

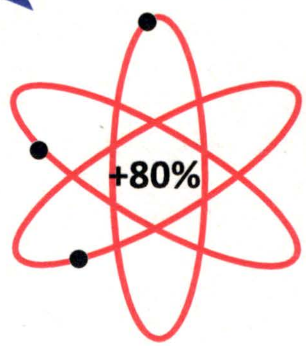
Notes: *(1) See chapter End-notes, item* ***E****. (2) See* **Uses***: Hybrid/Solar (3) Combination of boiler duct burners and superior load following ability of gas turbine*

CONCEPT

FINANCIAL: *Sustainability*



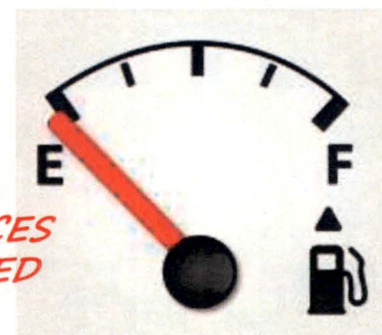
More Energy ✓



- ➢ MORE RESOURCES[1]
  - ✓ *Secure Future*
- ➢ ENERGY INDEPENDENCE
  - ✓ *All US Fuels*[2]
  - ✓ *Saves US Nuclear & Coal Industries*

ALTERNATIVES

RESOURCES DEPLETED



CONCEPT

Note: *(1) Renewables cannot meet all future needs due to limited available locations and intermittent nature of resource. (2) Currently, US imports majority of needed uranium –* **Ref. 16**.

FINANCIAL: *Cost Breakdown*

PLANT BUDGETARY ESTIMATE[1]	
ELEMENT	PERCENT OF EPC
Reactor Systems	44%
Power Systems	21%
Water Systems	3%
Instrument & Control	3%
Electric Plant	5%
Switchyard	2%
Buildings & Structures[2]	19%
Civil Works	3%
Total	100%
Reactor Block = 72%	Power Block = 28%

- **SOUND APPROACH**
  - ✓ *Consistent with Historical Data*

__Notes__: ***(1)*** *Developed using Bill-of-Quantity methodology routinely used to estimate build cost of combined-cycle power plants.* ***(2)*** *Equipment foundation costs included with component estimates.*

CONCEPT

FINANCIAL: *Contrast*

/Fundamentals – *Production*

	Fuel	O&M[1]	Fixed[2]	Capacity[3]	Life[4]	
Gas	~60%	~4%	~36%	90%	30	Mostly Fuel Costs
HYBRID/GAS	~46%	~4%	~50%[6]	90%	40	
Coal	~26%	~6%	~68%	90%	40	
HYBRID/ COAL-GAS	~20%	~8%	~72%	90%	40	
Coal Gas	~19%	~8%	~73%	90%	40	
Large Nuclear	~8%	~2%	~90%	90%	40+	Mostly Fixed Costs
HYBRID/ ALL NUCLEAR	~7%	~5%	~88%	90%	40	
Small Nuclear	~6%	~10%	~84%	90%	40+	
Wind[5]	0 %	~5%	~95%	28%	20	
Solar[5]	0%	~5%	~95%	25%	20	

Notes: *(1) Variable operations & maintenance costs. (2) Includes profit, debt repayment, personnel, property taxes, fees. (3) Expected yearly generation - industry data. (4) Expected project life, years. (5) Capacity factor, see chapter End-notes, item C. (6) Hybrid staffing based on 6-shift rotation: 1 shift-manager and 4 operators plus 3 security officers per shift. Day staff ~75.*

CONCEPT

FINANCIAL: *Contrast*

/Fundamentals – *Build (Capital) Costs*

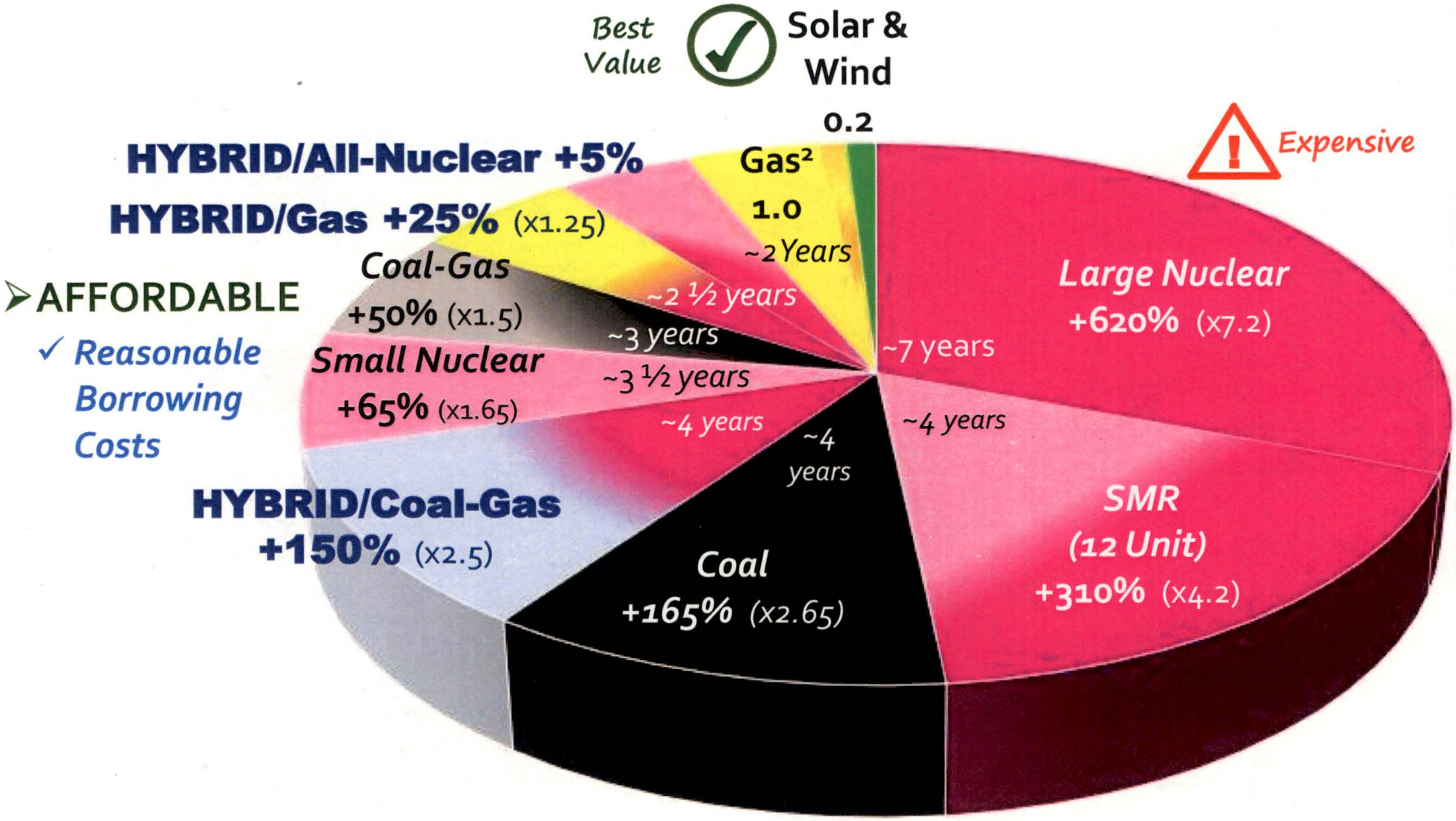
	PLANT TYPE	OUTPUT mW	EPC[1] $/kW	"All-In"[2] $/kW	
Best Value ✓	*Gas*	925	$925	$1150	*Fossil*
	HYBRID/Gas	950	$1100	$1485	*Nuclear & Fossil*
Renewable	*Solar*[3]	100	$1810	$2170	
Renewable	*Wind*[3]	100	$1910	$2290	
	Coal	895	$2225	$2890	*Fossil*
	HYBRID/Coal-Gas	980	$2200	$3000	*Nuclear & Fossil*
	Coal-Gas	465	$2900	$3800	*Fossil*
Nuclear	HYBRID/All-nuclear	310	$3000	$4200	
Nuclear	*Large Nuclear*	1115	$5500	$7700	
Nuclear	*SMR (12 units)*[5]	660	$6105	$8845	
Nuclear	*Small Nuclear*[4]	185	$7650	$10705	
Nuclear	*SMR (1 unit)*[6]	55	$9490	$13185	⚠ *EXPENSIVE*

Notes: ***(1)*** *Approximate Engineer, Procure, Construct (EPC) cost. Conventional plant EPC costs developed by author from various industry sources and data.* ***(2)*** *Includes Owners Costs and short-term construction financing.* ***(3)*** *See Chapter End-Notes, item* ***B*** *for EPC cost basis.* ***(4)*** *Scaled to large nuclear – see chapter End-note, item* ***H****. (5) 12 modules at 46 MW(e) each, scaled to large nuclear.* ***(6)*** *Scaled to 12 unit Small Modular reactor (SMR).*

CONCEPT

FINANCIAL: *Contrast*

/Build (EPC) Dollar Cost[1]

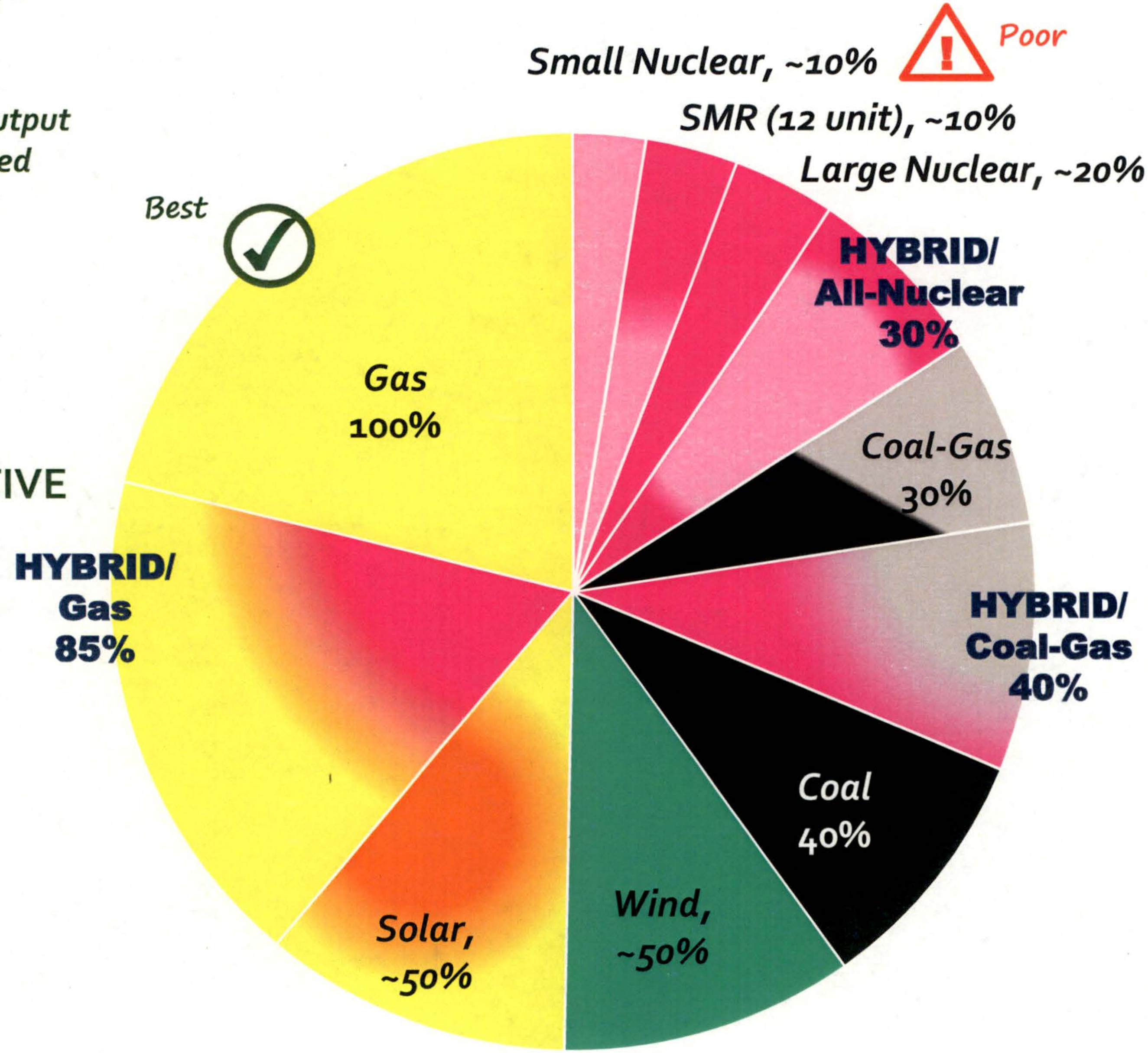


<u>Notes:</u> ***(1)*** *Approximate Engineer, Procure, Construct (EPC) price for plant outputs of* **Financial: *Contrast/Fundamentals –Build (Capital)*** *– excludes Owners costs.* ***(2)*** *Natural gas plant EPC cost ~$925 Million.*

CONCEPT

FINANCIAL: *Contrast*
/Capital Efficiency*

** Relative Power Output per Dollar Invested Building Plant*



➢COST EFFECTIVE

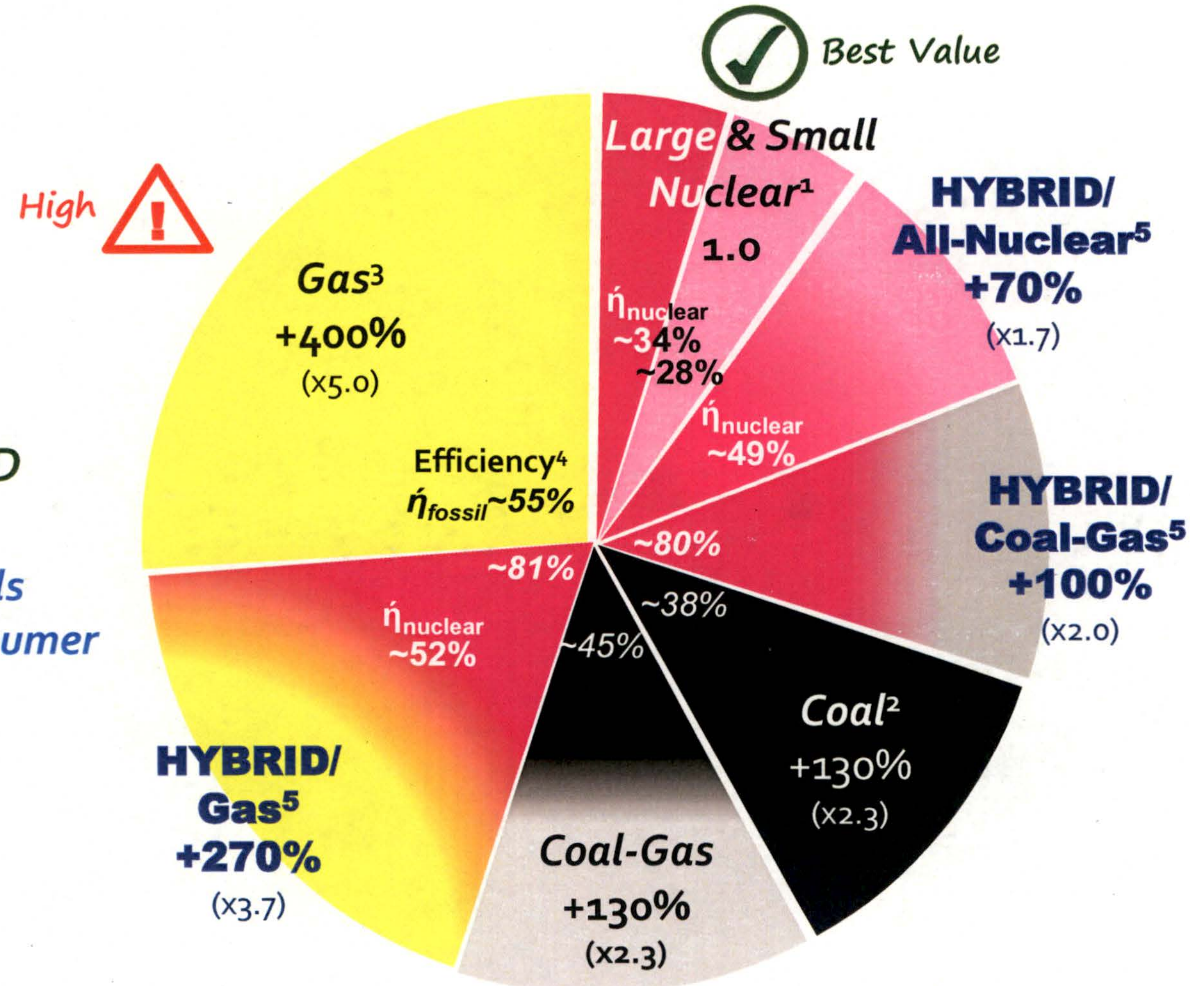
✓*Reasonable Market Risk*

CONCEPT

 Rev. A

FINANCIAL: *Contrast*
/US Fuel Costs

➢ *RISK REDUCED*
- ✓ *Hedged – Uses Two Fuels*
- ✓ *Protects Consumer & Investor*



Notes: ***(1)*** *Nuclear Fuel ~$1 per million British Thermal Unit (MMBtu)*. ***(2)*** *Coal prices typical delivered US Mid West.* ***(3)*** *Gas typical US Mid West, including transportation & fees.* ***(4)*** *Efficiencies, see chapter End-notes, item* ***D***. ***(5)*** *Hybrid nuclear fuel cost -- see chapter End-notes item* ***F.***

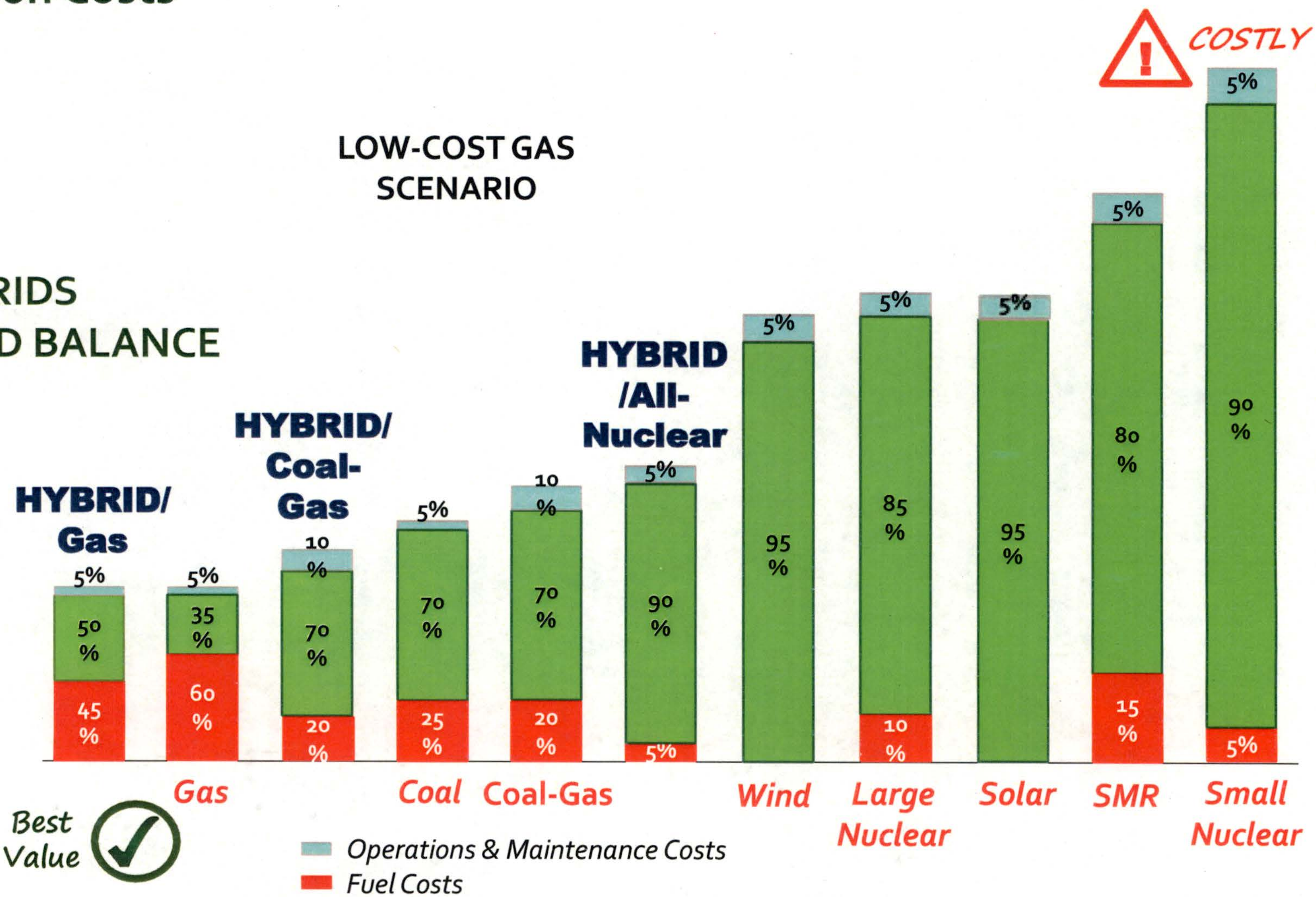
CONCEPT

FINANCIAL: *Contrast*
/Production Costs

Hybrid-Nuclear Energy

LOW-COST GAS SCENARIO

➢ HYBRIDS GOOD BALANCE

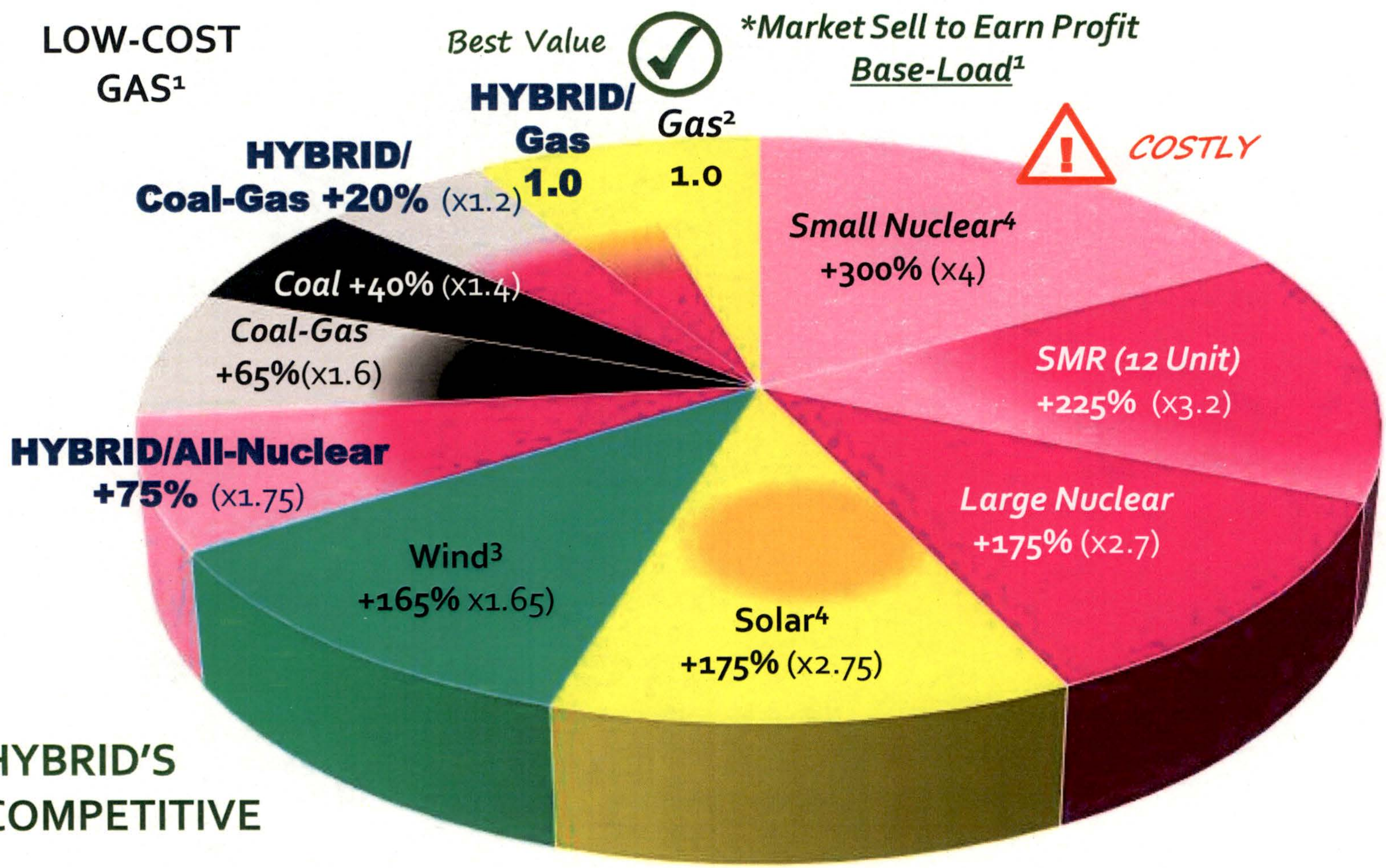


Note: *(1) Evaluated using IPP Model @ 90 % capacity factor, Wind & Solar ~28 & 25% respectively.*

CONCEPT

FINANCIAL: *Contrast*

/Energy Price*



➢HYBRID'S COMPETITIVE

Notes: (1) *Plant outputs and "All-in" costs per* **Financial: *Contrast/Fundamentals –Build (Capital) Cost*** *using IPP model, see Chapter End-notes, item* ***(A)***. *The objective of the IPP Model is to assess the fundamental and inherent financial competitiveness of a technology.* **(2)** *Natural Gas plant power price ~$55 per Megawatt-hour, low-cost gas $5/MMBTU.* **(3)** *Wind, US Midwest .* **(4)** *Solar US West.*

$ CONCEPT

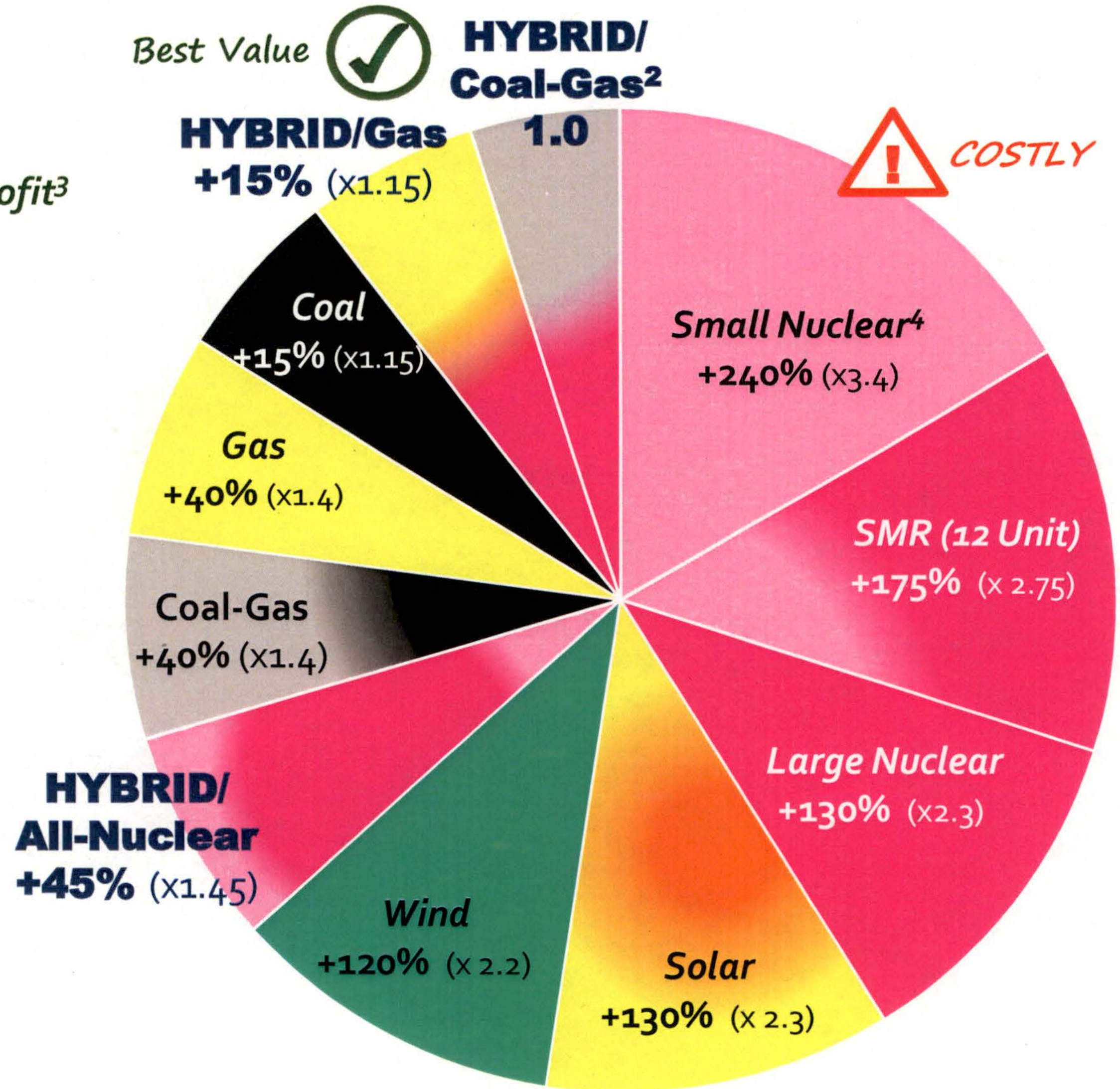
FINANCIAL: *Contrast*

/Energy Price*

**Market Sell to Earn Profit[3]*
Base-Load

HIGH-COST GAS[1]

➢HYBRID'S COMPETITIVE

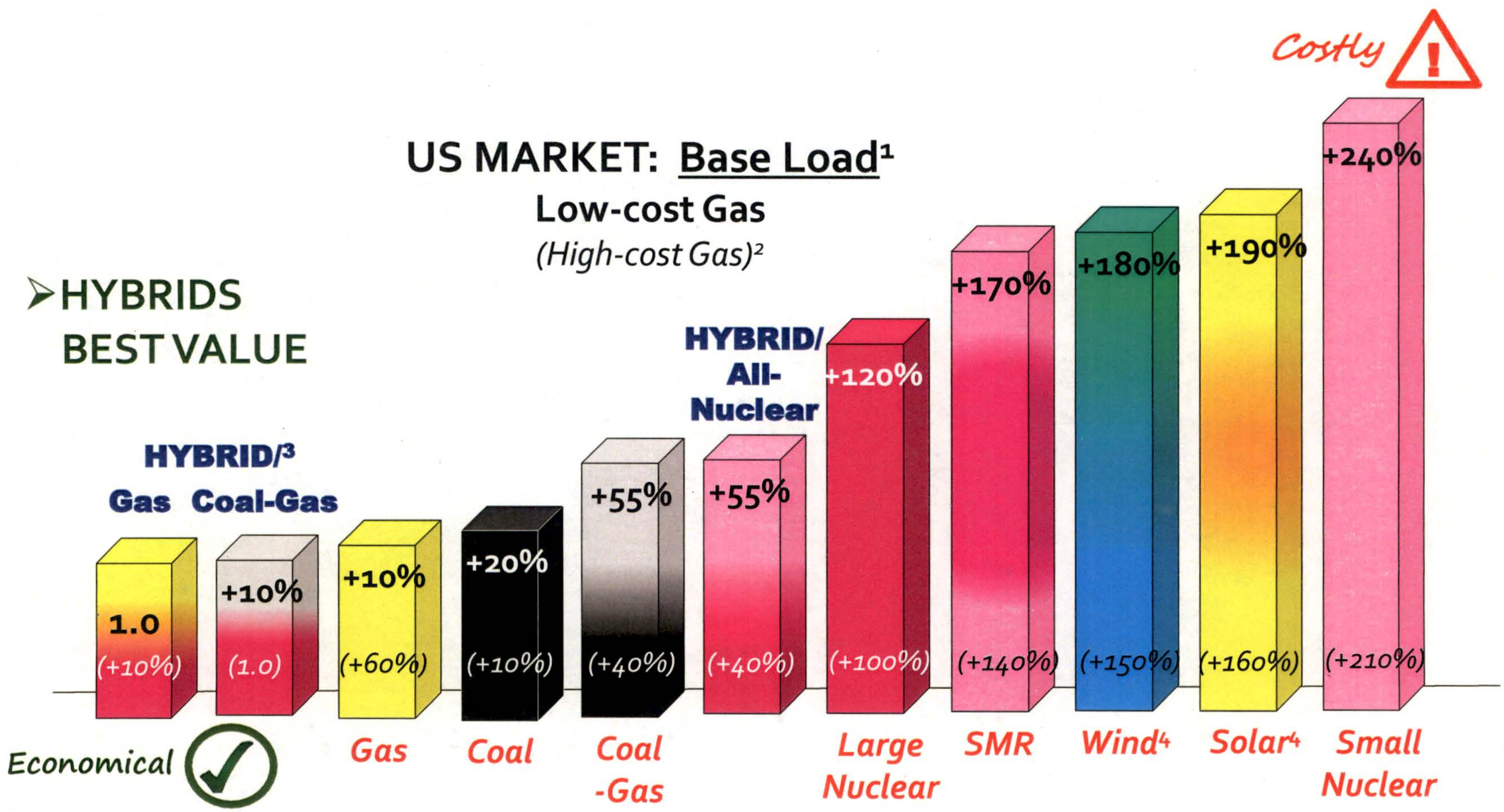


Notes: ***(1)*** *Gas $10/MMBTU.* ***(2)*** *Hybrid/Coal-gas plant power price ~$66 per Megawatt-hour.* ***(3)*** *IPP model, see Chapter End-Notes, item* ***A***

CONCEPT

FINANCIAL: *Contrast*

/Leveled Cost of Energy



<u>Notes:</u> ***(1)*** *Evaluated using IPP Model – see chapter End-Notes, item* ***A****. Average power price over life of plant.* ***(2)*** *$5 & $10/MMBTU respectively.* ***(3)*** *Low-cost gas: Hybrid/Gas LCOE power price ~$45/MW-hour; High-cost gas: Hybrid/Coal-Gas LCOE power price ~$65/MWh.* ***(4)*** *See chapter End-notes, items* ***B*** *&* ***C****.*

CONCEPT

FINANCIAL: *Contrast*

/Leveled Cost of Energy

Hybrid-Nuclear Energy

US MARKET[1] – Base Load/ *(Load Following[2])* Low-cost Gas

HYBRIDS/				Gas[1] 925 MW(e)	Coal 895 MW(e)	Coal-Gas 445 MW(e)	Wind[3]	Solar[3]	NUCLEAR		
All-Nuclear		GAS ~950 MW(e)	COAL 980 MW(e)						Large 1115 MW(e)	SMR[3] 652 MW(e)	Small 185 MW(e)
Micro	Small										
10 MW(e) $320 15 MW(e) $160 25 Mw(e) $130 45 Mw(e) $100	120 MW(e) $80 170 MW(e) $75 300 MW(e) $70	$45 *($75)*	$50 *($110)*	$50 *($70)*	$55 *($115)*	$70 *($150)*	$125 *($125)*	$130 *($130)*	$100 *($265)*	$130 *($300)*	$200 *($390)* *Too Costly*

Good Value

Best Value is Base Load — *Adaptable to Load-Following*

Not Viable as Load-Follower

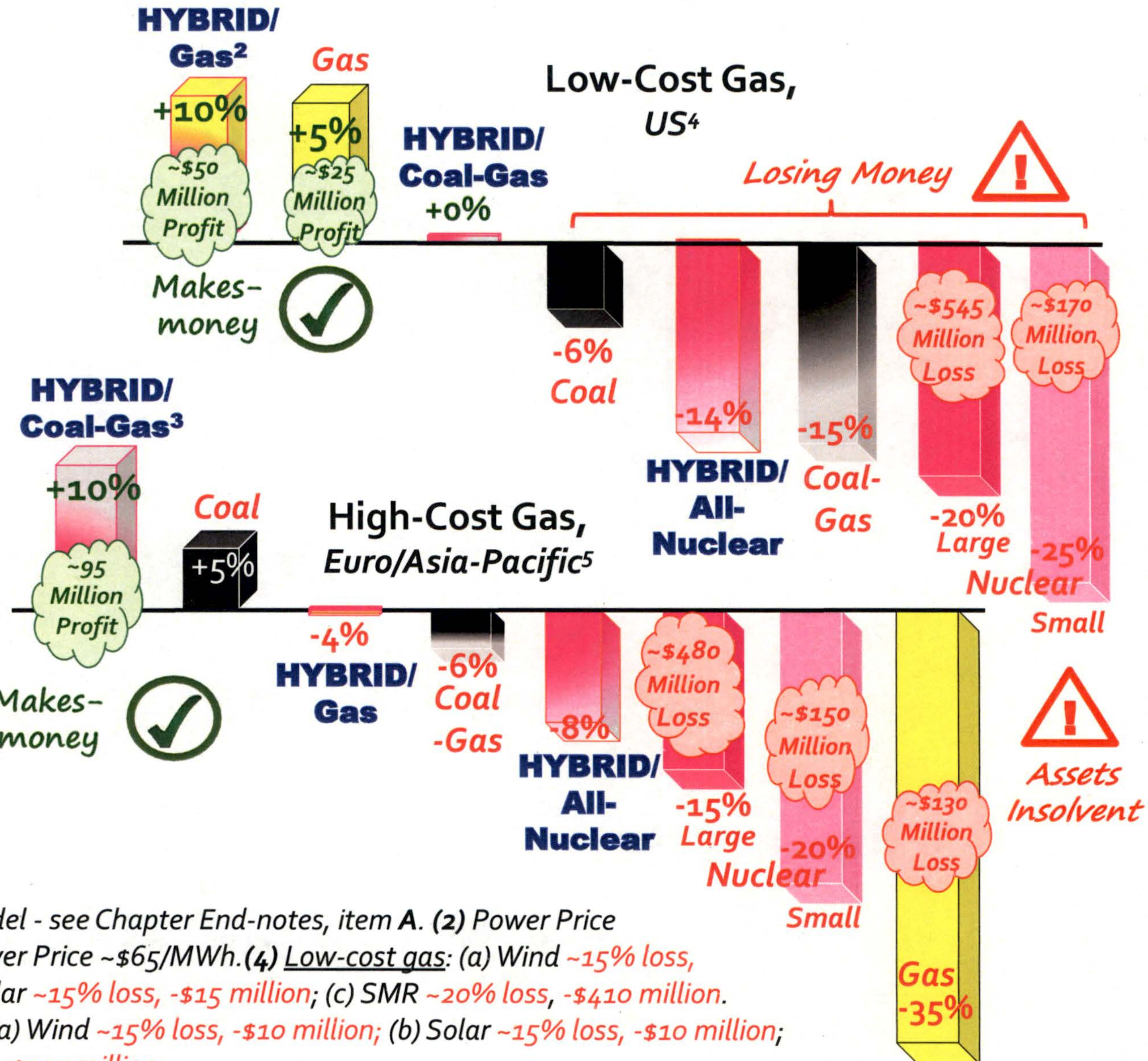
Notes: ***(1)*** *Evaluated using IPP Model – see chapter End-notes, item* ***A.*** ***(2)*** *Thermal plants operating at 50% capacity.* ***(3)*** *Not baseload machines and unreliable, LCOE misleading.* ***(3)*** *12-module NUSCALE plant.*

CONCEPT

FINANCIAL: *Contrast* /Marketplace*

** EXPECTATIONS-*
Base Load
Lowest Cost Producer Sets Price/Profit[1]

➢ HYBRIDS PROFITABLE
- ✓ *Key Reason to Deploy*
- ✓ *Economic Hedge:*
  - Carbon Taxes
  - Volatile Gas Prices



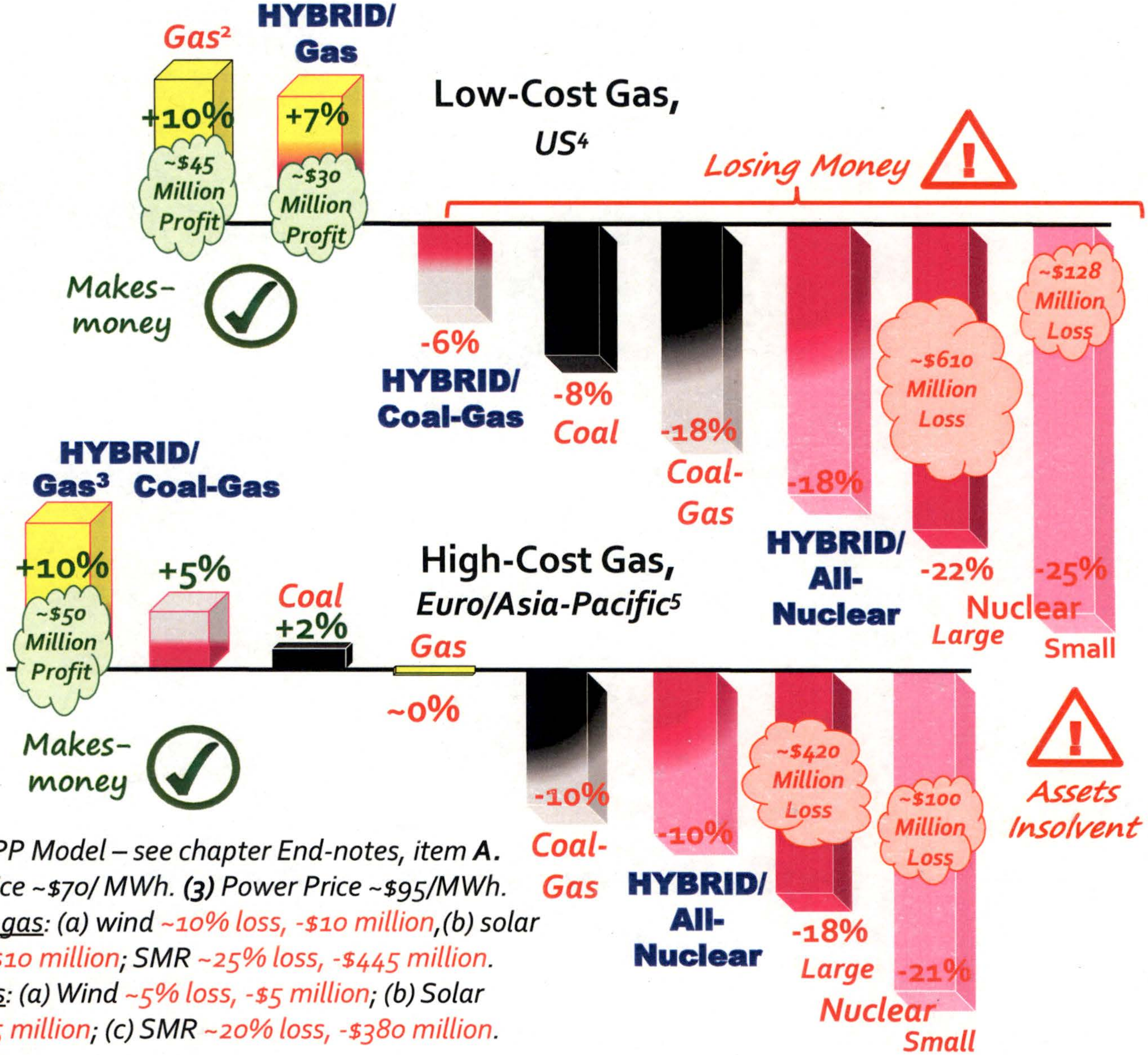
Notes: ***(1)*** *IPP Model - see Chapter End-notes, item* ***A***. ***(2)*** *Power Price ~$55/MWh.* ***(3)*** *Power Price ~$65/MWh.* ***(4)*** *Low-cost gas: (a) Wind ~15% loss, -$10 million; (b) Solar ~15% loss, -$15 million; (c) SMR ~20% loss, -$410 million.* ***(5)*** *High-cost gas: (a) Wind ~15% loss, -$10 million; (b) Solar ~15% loss, -$10 million; (c) SMR ~15% loss , $340 million.*

CONCEPT

FINANCIAL: *Contrast*
/Marketplace*

**EXPECTATIONS-*
Grid Following
(50% Capacity Factor)
Lowest Cost Producer Sets Price/Profit[1]

➢ HYBRIDS PROFITABLE
- ✓ *Well Suited for Grid Support*
- ✓ *Good Hedge*



Notes: **(1)** *IPP Model – see chapter End-notes, item* ***A.*** **(2)** *Power Price ~$70/ MWh.* **(3)** *Power Price ~$95/MWh.* **(4)** *Low-cost gas: (a) wind ~10% loss, -$10 million, (b) solar ~10% loss, -$10 million; SMR ~25% loss, -$445 million. High cost gas: (a) Wind ~5% loss, -$5 million; (b) Solar ~5% loss, -$5 million; (c) SMR ~20% loss, -$380 million.*

CONCEPT

FINANCIAL: *Contrast*

/Energy Price (No Debt)[1]

➢ HYBRIDS GOOD For CONSUMER[1]

DEBT FREE	*Low-Cost Gas*	*High-Cost Gas*
HYBRID/Gas[2]	1.0	+60%
HYBRID/Coal Gas[2]	1.0	1.0
Gas	+15%	+110%
Coal	+20%	+20%
HYBRID/All-Nuclear	+40%	+40%
Coal-Gas	+50%	+50%
Wind	+90%	+90%
Large Nuclear	+110%	+110%
Solar	+110%	+105%
SMR	+140%	+150%
Small Nuclear	+210%	+220%

Best Values (Low-Cost Gas: HYBRID/Gas, HYBRID/Coal Gas, Gas, Coal)

Best Value (High-Cost Gas: HYBRID/Coal Gas)

Too Expensive (Low-Cost Gas: Wind, Large Nuclear, Solar, SMR, Small Nuclear)

Too Expensive (High-Cost Gas: Wind, Large Nuclear, Solar, SMR, Small Nuclear)

Notes: ***(1)*** *Evaluated using IPP Model – see chapter End-notes, item **A**.* ***(2)*** *HYBRID/Gas ~$38/MWh.* ***(3)*** *HYBRID/Coal-Gas ~$37/MWh.*

CONCEPT

FINANCIAL: *Contrast*

/Cost Overruns

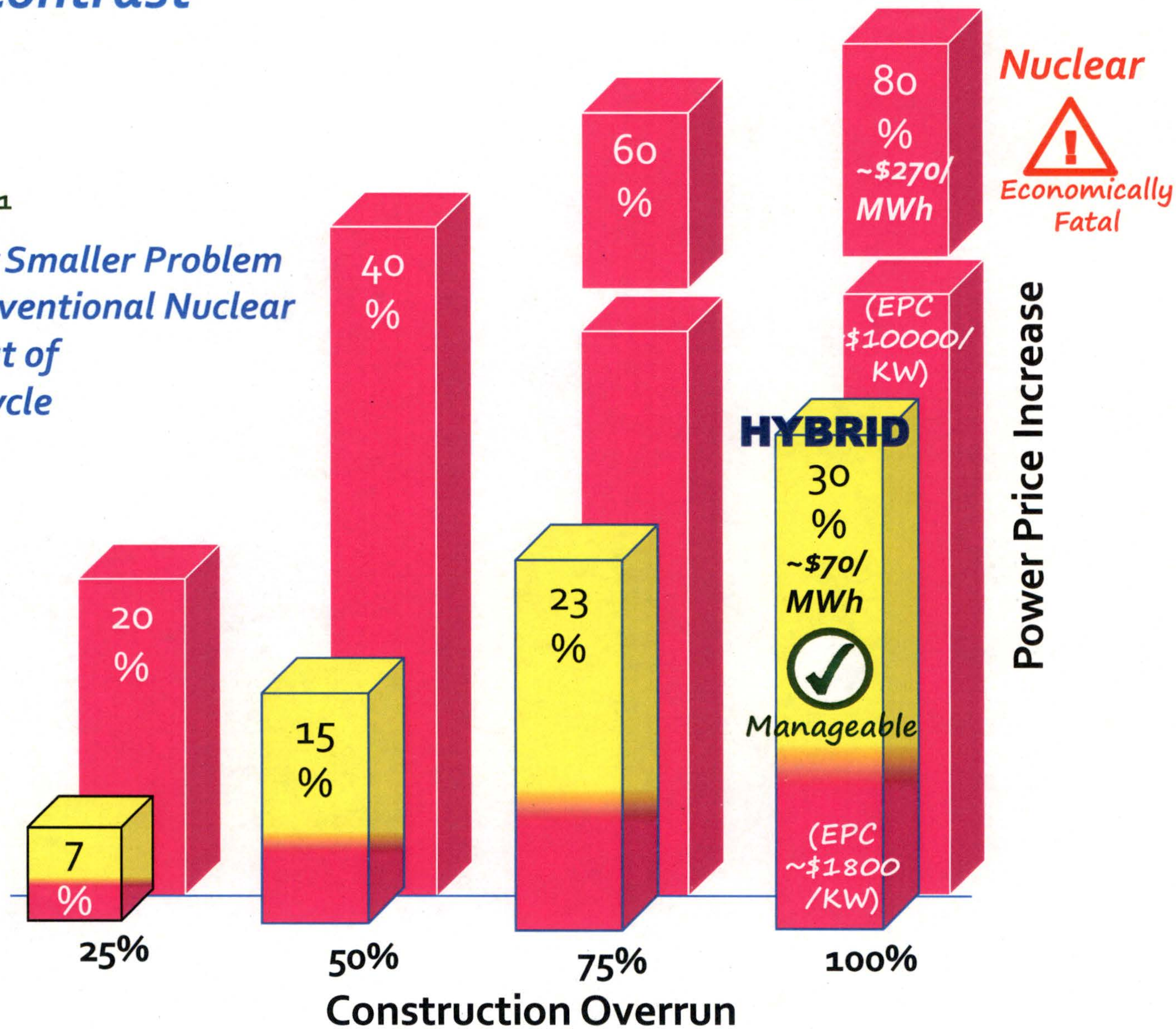
- **RISK EASED**[1]
  - ✓ *Significantly Smaller Problem Than for Conventional Nuclear*
  - ✓ *Helpful Assist of Combined-Cycle*

Nuclear

Baseline
~$150/MWh
~$5500/KW

Baseline
~$55/MWh
~$1100/KW

HYBRID



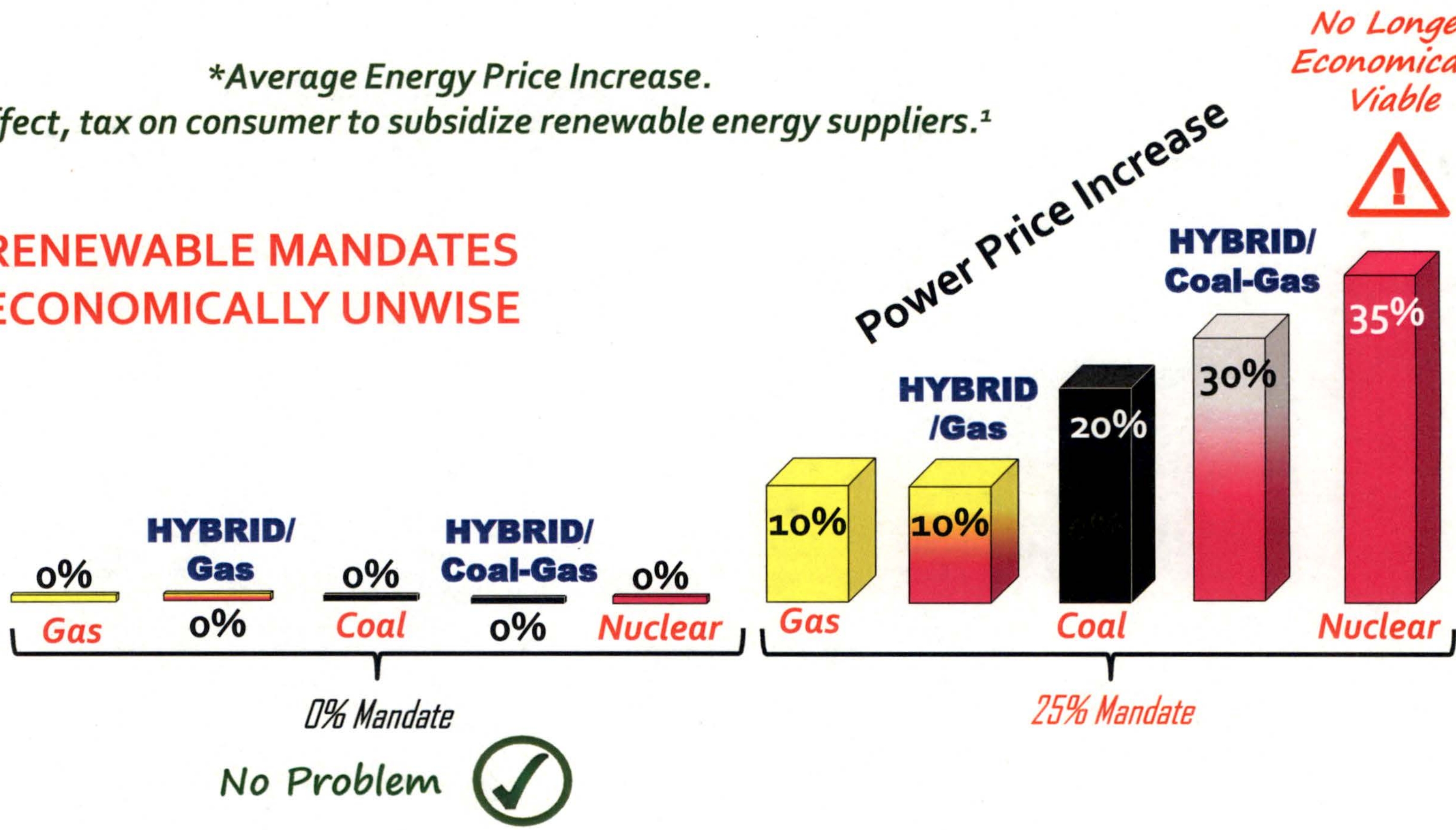
<u>Note</u>*: (1) Historically, reactor plant costs overruns can be a problem, with initial forecasts off by factors of typically about 50%. However, Power Block (combined-cycle) costs are very stable.*

CONCEPT

FINANCIAL: *Contrast*
/Green Energy Fee*

**Average Energy Price Increase.*
In effect, tax on consumer to subsidize renewable energy suppliers.[1]

RENEWABLE MANDATES ECONOMICALLY UNWISE



Note: *(1) Renewable energy mandates cause output reductions in other more capable power plants. As long as renewables more expensive than baseline plants , power prices must rise.*

CONCEPT

FINANCIAL: *Contrast*

/Renewable Subsidies

Renewable Energy
Tax Incentives +$50 Billion[1]

Benefit to Climate negligible, most equipment supplied from overseas, energy prices higher, impact on environment actually unhelpful.

<u>Note</u>: ***(1)***. *Total incentives from 2005 thru 2015 per* **Ref. 66**. *Continues to grow ~ 5 billion per year per eia.gov.* ***(2)*** *Cost of tax-based incentives is lost Federal revenue that other taxpayers (current or their children and their grandchildren) must replace as US constantly borrows more money to pay ever burgeoning debt. Basic economics.*

CONCEPT

FINANCIAL: *Contrast*
/ECO Capital Efficiency*

Low-Cost Gas

➢ HYBRIDS GOOD for CONSUMER & ENVIRONMENT

⚠ *But Renewable Mandates Unhelpful*

- *Only Serves to Drive Up Cost to Consumer with no Meaningful Reduction in CO_2*

★ = Best, ✓ = Average, ✗ = Needs Work.

* CO_2 Reduction plus Energy Price[1]	ή[1] Baseline Score	Rating	ή[2] 25% Mandate	Rating[3]
HYBRID/Gas	89%	★	84%	✓+
HYBRID/All-Nuclear	82%	✓+	72%	✓
Gas	81%	✓+	77%	✓+
Large Nuclear	73%	✓+	63%	✓
HYBRID/Coal-Gas	71%	✓	58%	✓
SMR (12 unit)	69%	✓	62%	✓
Small Nuclear	63%	✓	60%	✓
Wind[4]	61%	✓	54%	✓-
Solar[4]	61%	✓	53%	✓-
Coal	41%	✗+	31%	✗
Coal-Gas	35%	✗	25%	✗

__Notes__: ***(1)*** *Efficiency of 100% = lowest power price ($/MWh) + 100% CO_2 removal.* ***(2)*** *25 % renewables causes 65% capacity factor for all others.* ***(3)*** *Relative to baseline. (4) Augmented by gas to reach 90% capacity factor. If only used for peaking support, Eco-Capital Efficiency Wind & Solar ~69% (check)*

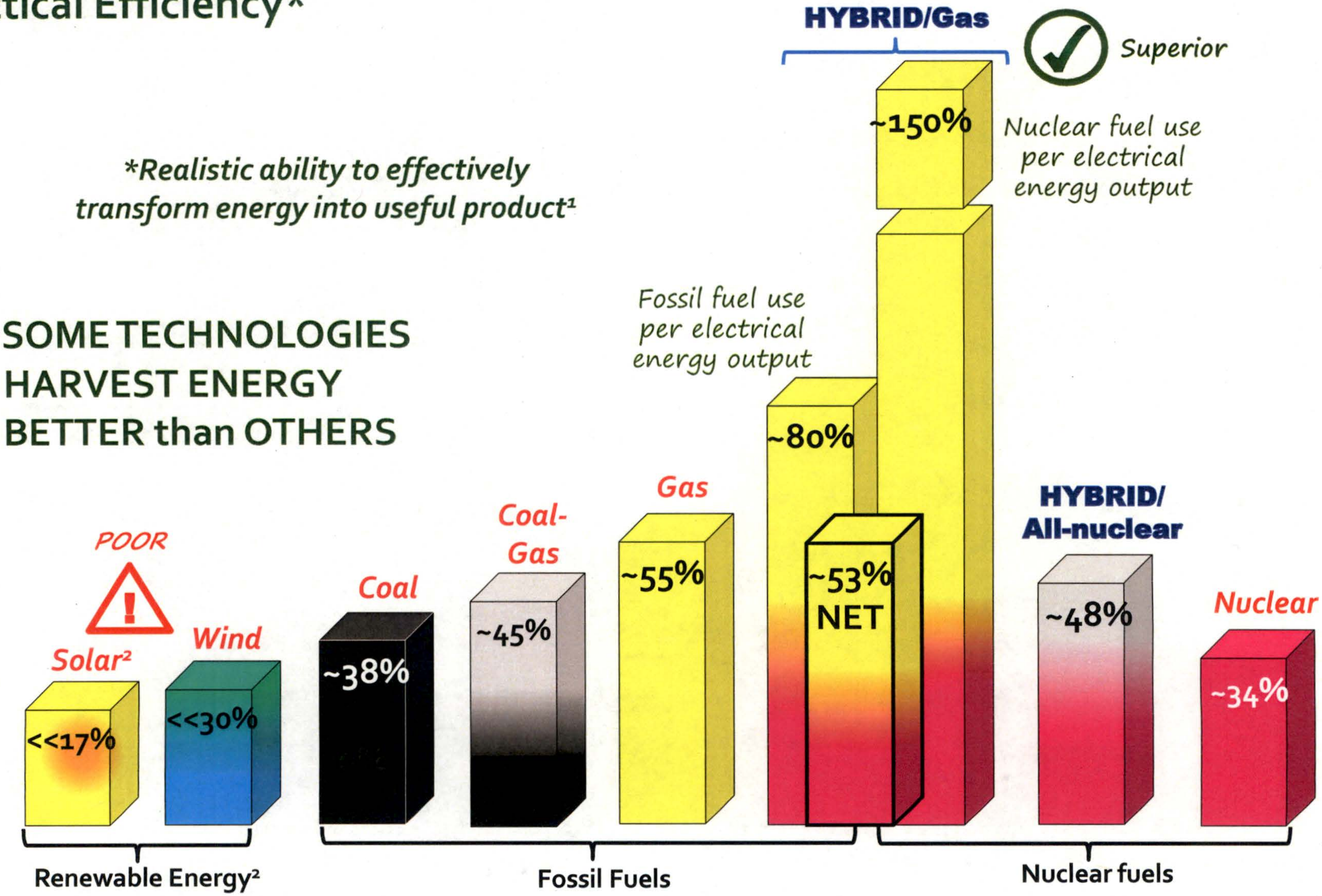
CONCEPT

FINANCIAL: *Contrast*

/Practical Efficiency*

**Realistic ability to effectively transform energy into useful product[1]*

- **SOME TECHNOLOGIES HARVEST ENERGY BETTER than OTHERS**

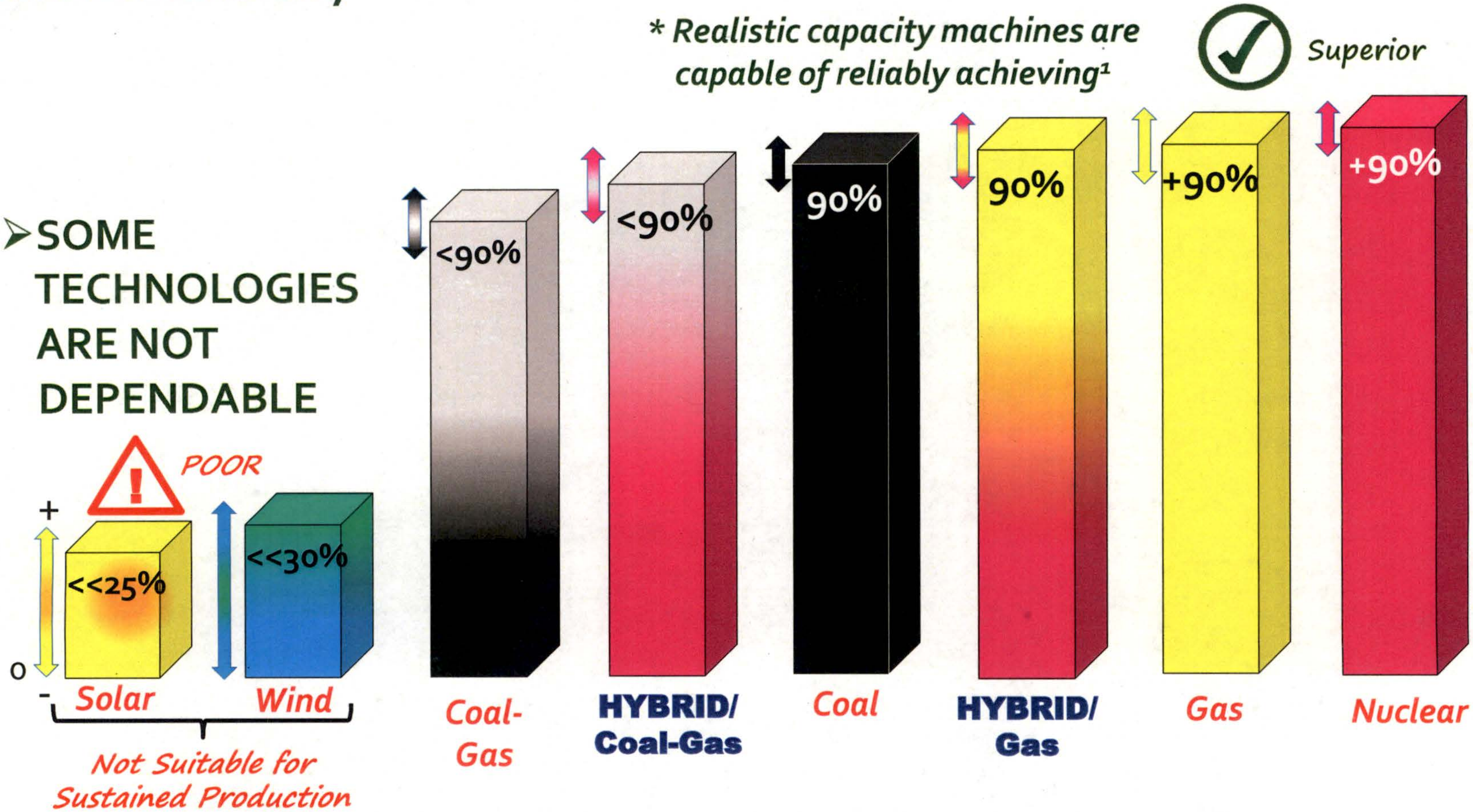


Note: *(1) {Net Electrical Power Out} / {Fossil or Nuclear Power In}. (2) Varies significantly with location & environmental conditions* - **Refs. 39 & 40.** Greatly complicates investment, absent substantial subsidies.

CONCEPT

FINANCIAL: *Contrast*
/Practical Reliability*

➢ SOME TECHNOLOGIES ARE NOT DEPENDABLE



Note: *(1) Measure of a technology's inherent stability or availability. Related to capacity factor but not data reported by agencies such as the US Energy Information Administration which provides marketplace capacity factors as opposed to inherent capability. Steam plants somewhat impacted by heat sink temperature and gas turbines impacted inlet air temperatures. Renewable energy severely impacted by environmental conditions and not capable of sustained production - zero output a fact-of-life. Seriously compromises profitability, absent subsidies. Stated differently, the pure financial market value of renewable energy is not that great.*

CONCEPT

FINANCIAL: *Contrast* /Investment Risks

➢LESS DANGER to PROFITS

	Gas	HYBRID[1]	Coal	Nuclear
Construction	Low	Medium To Low	Medium	High
Revenue	High To Low[3]	Low	Medium	High[4] to Medium
Regulatory/ Government	Low	Medium To Low	High	High
Politics[2]	Medium	Medium	High	High
Bottom Line	GOOD	MAYBE	RISKY	TOO RISKY

Notes: *(1) High-reliability version of Hybrid reduces risk. (2) Free market badly distorted by government mandate. Taxpayer & consumer forced funding severely impacts profitability, grid stability, & rate payer costs. (3) Cost of gas. (4) Competeviness. (5) Absent subsidies/mandates, renewables too risky.*

CONCEPT

FINANCIAL: *Rankings*
/Nuclear Plants

Category[1]	HYBRID	*Gas Reactors*	*Water Reactors*
Build Cost, $/KW	★	✗+	✗
Capital Efficiency	★	✓	✗
Fuel + Volatility	✗	✓+	★
Power Price	★	✗+	✗
Revenue[2]	★	✗+	✗
Profitability	★	✗+	✗
Sales Potential	★	✗	✗
ECO Efficiency	★	✓	✗
Risk	★	✗	✗
NET[3]	✓+	✗+	✗

★ = *Best*, ✓ = *Average*, ✗ = *Needs Work.*

➢ HYBRID VERY GOOD INVESTMENT

✓ ***Best for Stakeholders & Consumer***

<u>Notes</u>: ***(1)*** *Scoring relative to each other.* ***(2)*** *Sources & availability.* ***(3)*** *Average of categories.*

CONCEPT

FINANCIAL: *Rankings*

/Power Plants

Category[1]	HYBRID	*Gas*	*Coal*	*Solar/ Wind*	*Nuclear*
Build Cost, $/KW	★-	★	✓+	✓	✗
Capital Efficiency	✓+	★	✗+	✗	✗
Fuel + Volatility[4]	✗+	✗	✓+	✓	★
Power Price[4]	★	★	✓+	✗+	✗
Revenue[2]	★	✓	✗+	✗	✗
Profitability[3]	★	✓+	✗	✗	✗
Sales Potential	★	★-	✗+	✓	✗
ECO Efficiency	★	✓+	✗+	✓-	✓+
Risk	★	★-	✗+	✓	✗
NET[5]	✓+	✓+	✗+	✗	✗

★= Best, ✓= Average, ✗= Needs Work.

- HYBRID SOUND VENTURE
  - ✓ *Protects Customers & Plant Owners*

<u>Notes:</u> *(1) Relative scoring. (2) Sources & availability. (3) **Mandate and** subsidy free marketplace. (4) Includes gas supplementing renewables to achieve sustained baseload production. (5) Category averages.*

CONCEPT

FINANCIAL: *End-Notes*

A. Independent Power Producer (IPP) Model

- *Owners Equity 35% of Project Cost with 10% return on invested capital.*
- *Long-term note @ 8% for 15 years on borrowed capital.*
- *Short-term note at 6% for construction period – bridge loan for long duration projects.*
- *Build cost, i.e. Engineer, Procure & Construct (EPC) project costs as per text. Built in US Midwest. EPC construction costs = Direct labor + Equipment/material/consumables. EPC Project Costs = Construction + Overhead + Contingency + Profit.*
  EPC Project Cost Elements as follows:
  i. Construction portion of EPC project cost: ~73% fossil & renewable; 65% nuclear.
  (a) Direct Labor portion of EPC construction costs: ~18%.
  (b) Equipment/materials, rentals, & consumables portion of direct EPC construction costs: ~82%.
  ii. Overhead (in-directs) portion of EPC project cost: ~15%.
  iii. Contingency portion of EPC project cost: ~7% fossil & renewable; 12% nuclear.
  iv. Profit portion of EPC project cost: ~5% fossil & renewable; 8% nuclear.
- *Fuel Costs as noted in text.*
- *Owners Costs (% of EPC project cost) for development, licensing, permitting, land acquisition, taxes, etc.*
  Nuclear: ~35%; Fossil: ~25% ; Renewable: ~20%
- *Net Project Cost = Owner + EPC Project*
- *Plants located within 50 miles of load centers. For 345 Kilovolt lines, losses ~4%/100 miles.*
- *No subsidies, mandates or tax write-offs of any kind.*

This information represents typical expectations, as amassed from various industry sources and experience. The information is considered reasonably accurate for the broad comparative purposes of this work.

B. Solar & Wind*. Initial Solar EPC cost $1450/KW using* **Ref. 15** *for large scale utility installations. Initial Wind EPC cost ~$1600/KW using* **Ref. 11.** *However, DOE laboratory estimates considered overly optimistic from a budgetary cost standpoint and as such 20% margin* added. *Additionally, renewable resources are assumed to be located about 100 miles from major load centers. Assuming 345 KV transmission lines, 2% line loss employed in cost calculations.*

The power price forecasts for renewable energy are optimistic in the sense that operation of the facilities does not necessarily occur when power is actually needed. For instance, wind in the Midwest tends to occur at night in the winter while being somewhat calm during the day in the summer. This means that the financial market value of renewable energy will likely not support investment requirements, absent heavy subsidies and mandates.

*C. **<u>Solar & Wind Capacity Factors</u>** These machines generally report panel & generator nameplate capacity factors, as opposed to customary values (i.e. net generation = gross output minus station loads & losses). Since the machines generate DC power, the efficiency of inverters (~92% but varies with temperature and output) and step-up transformers (~98%) must be included. Solar panel degradation ~0.5%/year (**Ref. 40** "rule of thumb") or ~93% at end of 15 years lifetime; average ~97%. Wind turbines also face degradation, ~0.9%/year over a 15 year lifetime - **Ref. 38.** More realistic capacities factors follow:*

- *Wind capacity factor: ~33% {US Midwest per **Ref. 10** }*(0.92)*(0.98)*(.96)*(.98 line loss factor) or ~ **27%***
- *Solar capacity factor US: ~29% {US West per **Ref. 10**} *(0.92)*(0.98)*(.97)*(.98 line loss factor) or **~24.5%**.*

Traditional capacity factors (gross output minus in-house loads) are utilized with all the other power plants of this text.

*D. **<u>Gas Turbine Efficiency & Output</u>** Gas turbine performance is generally reported by manufacturers for "new & clean" machines using lower-heating value (LHV) fuel while operating at sea level and at an ambient temperature of 59 °F . Actual efficiency and output will not be that good, as explained below.*

- *Fuel Energy Content. Natural gas is sold on the basis of the fuel's total energy content, i.e. Higher-Heating-Value (HHV). However, water vapor produced by combustion is not fully useful. Manufacturer's typically report efficiency assuming all the fuel's energy is used; i.e. efficiency reported on an LHV basis. More accurately, the fuel's HHV establishes "real-world" efficiency. The actual efficiency is about 90% of manufacturer's LHV reported values.*
- *Degradation. Manufacturer's report both efficiency & output for "new-and-clean" machines. However, expected output and efficiency are reduced several percent once the machine's operate for any appreciable time frame. Some (but not all) of this loss is recovered when the machines are overhauled – typically every 5 or so years.*
- *Ambient Conditions. Air temperature, elevation & inlet/outlet restrictions impact output and efficiency.*

The financial performance information of this text is based HHV fuel, "used" machines with typical inlet/outlet losses but at sea level and 59°F. Lower environment temperatures will increase output & efficiency for thermal plants.

*E. **<u>Renewable Energy</u>** The financial information of this chapter demonstrates that from a "free-market" perspective, renewable energy should be largely deployed only to support grid peaking needs. For instance, wind in the Midwest tends to occur at night in the winter while being somewhat calm during the day in the summer – **Ref. 63**. Using the resource for base-load, load-following or forced use by the grid only serves to inflict unnecessary financial hardship as net power prices and taxes (to support subsidies) must invariably rise.*

E. ***<u>Renewable Energy</u>*** ***(continued)*** *As observed by* **Ref 63**, *the financially irrational favoritism shown to renewable energy causes severe and unnecessary disruptions to the marketplace. Adding insult to injury, renewable energy has a minor impact on the planet's CO_2 levels, as any mathematical analysis clearly demonstrates. Also see* **ENVIRONMENTAL** *chapter end-notes, item* ***A***.

F. ***<u>Hybrid Fuel Cost</u>*** *Assay: field 0.17%, tails 0.25%, product 13% U_{235}. U_3O_8 @ $25.50/lbm, Conversion $5.85/kgU as UF_6, UF_6 $64/KgU as UF6, Separative Work Unit $50/SWU. 10% margin enrichment costs. Fabrication 45% of net cost.*

G. ***<u>Whole-Exceeds-Parts</u>*** *Capital cost about 35% lower while output about 25% higher relative to standalone reactor and gas turbine (1x1 combined-cycle).*

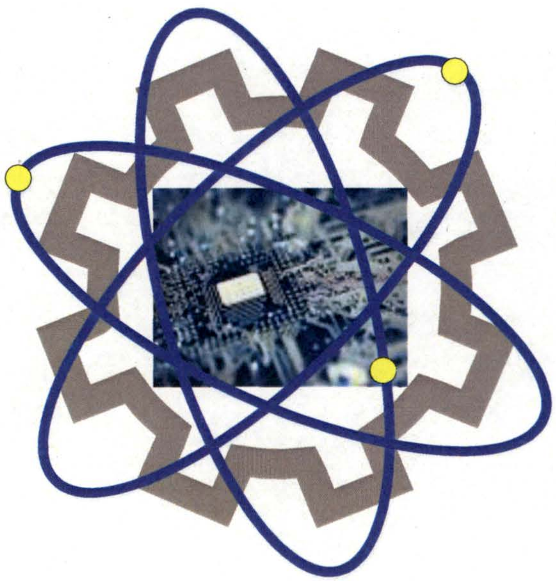
H. ***<u>Cost Scaling Factors</u>.*** *Gas turbines and wind turbines all rely on larger output and greater efficiency to reduce production costs. Large solar arrays are more efficient & cost effective than small roof-top installations. This trend is readily apparent for combined-cycle power plants where both installation and production unit costs become lower as machines become larger. Analyzing industry data (***Ref. 61***) yields the following relationship for combined-cycle gas turbine power stations:*

$$Y = (-0.222 * \ln(X) + 0.9892) * \text{Reference Large Plant Unit Cost in \$/KW}$$

Where X = (Smaller Plant Size)/(Reference Large Plant Size) *(correlation 0.984)*

This relationship is considered a reasonable approximation for nuclear plants.

The cost-saving mass-production philosophy behind Small Modular Reactors (which are smaller and less efficient than large nuclear units) is in stark contrast with historical reality. Unlike solar photovoltaic cells, complex SMR's are not commodity products. In addition, the historical data from the 1970's demonstrates that the cost of the reactor is around 10% of the total power plant cost. Also, the pricing of 1970 reactor components (for instance, those of Combustion Engineering Inc.) were based on mass scale factory production. At the time, nuclear power plants were cost competitive. However, the nuclear accident at Three Mile Island (TMI) created a massive influx of new regulations that predominately affected the that balance of plant, not the reactor per se. The massive increase in costs doomed nuclear power in the US, as evidence by the subsequent collapse of the US nuclear building program. Over-regulation has since continued more-or-less unabated, as discussed in the **ADAVANCED REACTOR ISSUES** *chapter.*



Historical Perspective

The evolution of energy production over the centuries has revolved around developing better machines to lower production costs, thereby increasing profitability.

The quest for ever greater efficiency by thermal power plants is driven by the Second Law of Thermodynamics. Energy can be more efficiently extracted with a greater temperature difference between the heat source and heat sink. As the heat sink temperature is generally relatively fixed, ever hotter heat source temperatures are required to noticeably increase efficiency. This entails the use of better materials to satisfactorily accommodate the associated higher temperatures.

The fundamental characteristics of a particular energy production process and associated materials place limitations on maximum heat source temperatures. Conventional water reactors are generally limited to working fluid temperatures of around 535 ^{O}F/280 ^{O}C, coal plants to around 1000 ^{O}F/538^{O}C while gas turbines are moving past 2900 ^{O}F/1600^{O}C

Increased heat source temperatures require some form of energy input which brings into play the cost of the fuel. The most efficient machine may not be the most cost-effective production method if fuel costs are too high.

HYBRID

➢PRACTICAL

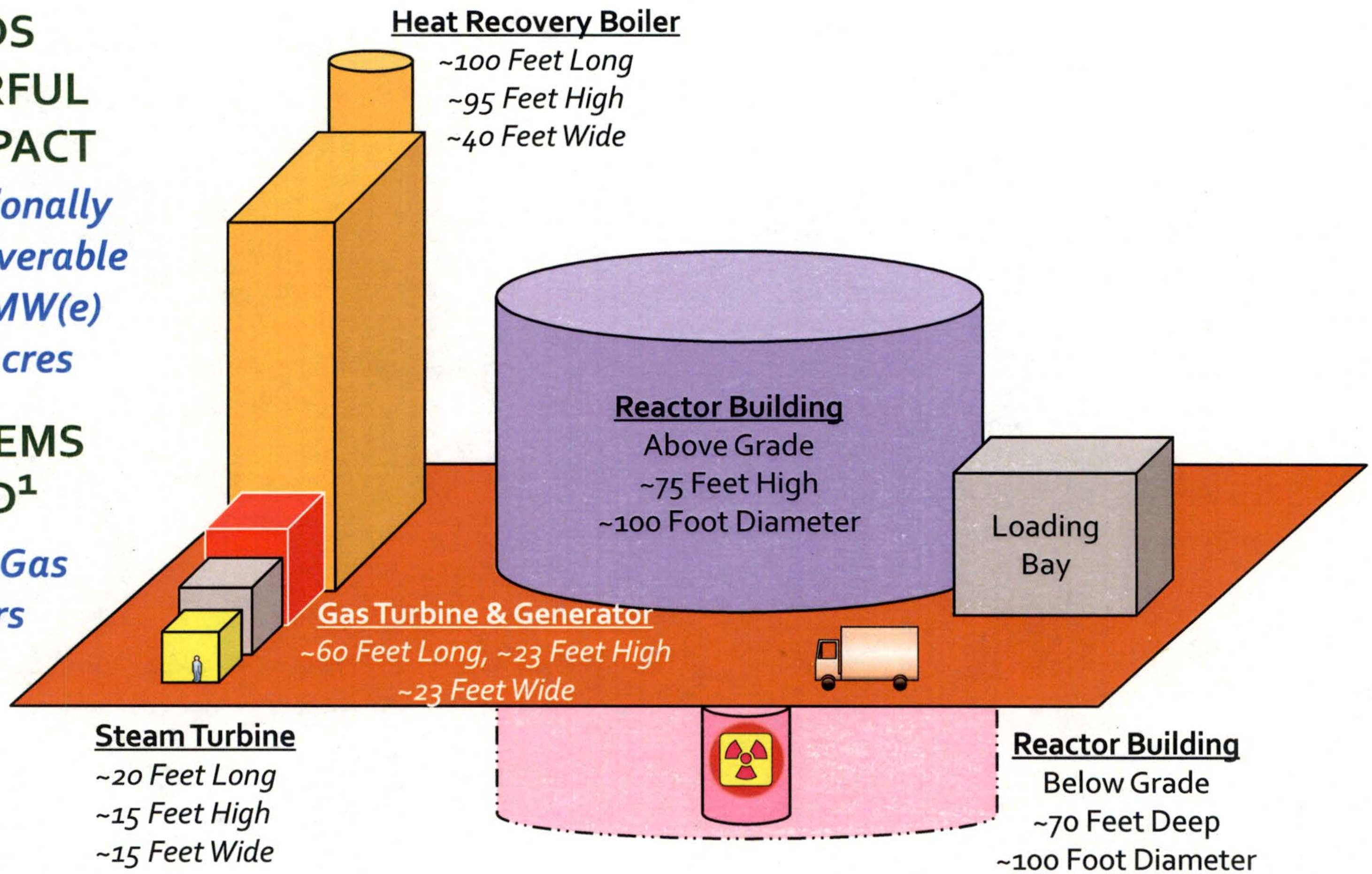
- ✓ Power Plant
- ⊘ Not physics Experiment

...And the free world

CONCEPT

TECHNICAL: *Overview*

- ➢ **HYBRIDS POWERFUL & COMPACT**
  - ✓ *Exceptionally Maneuverable*
  - ✓ *~1000 MW(e) on 25 Acres*
- ➢ **PROBLEMS SOLVED[1]**
  - ✓ *Earlier Gas Reactors*



CONCEPT

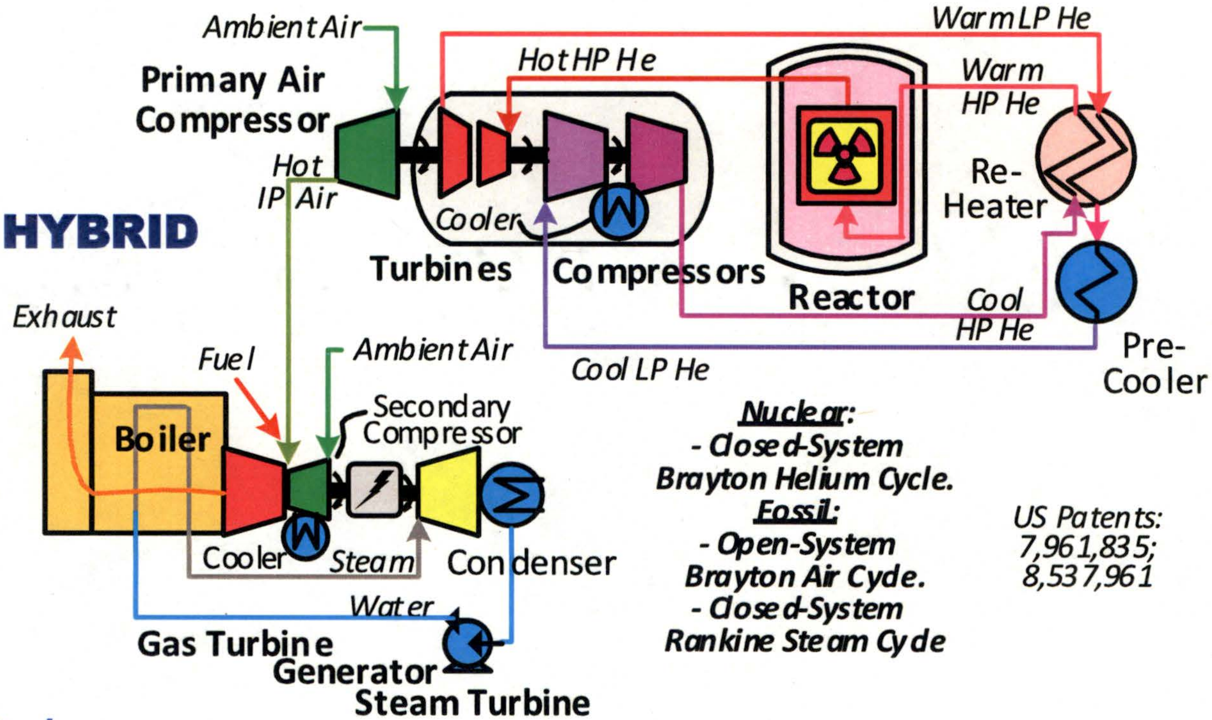
Note: *(1) See* **Appendix D** *for discussion.*

TECHNICAL: *Cycle Overview*

➢ QUANTUM LEAP

✓ *Simplicity, high-reliability, ease of operation, low-build-cost of combined-cycle power plant integrated with passively fail-safe, very efficient Helium gas reactor.*

HYBRID

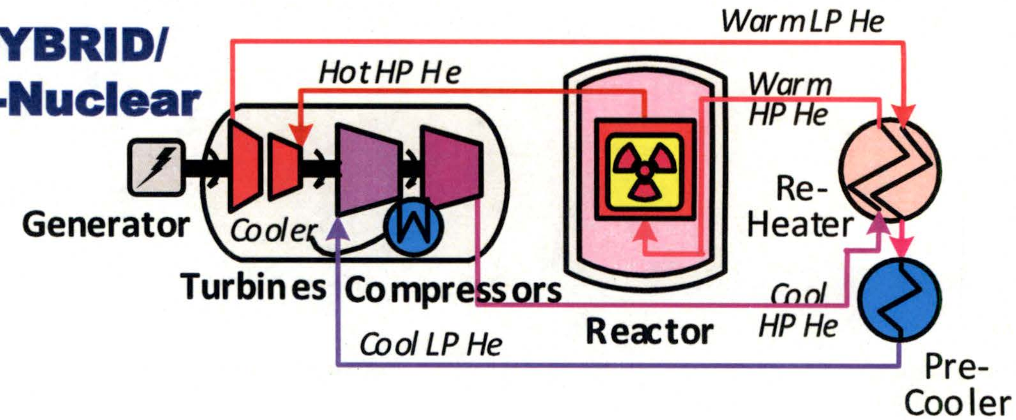


Nuclear:
- *Closed-System Brayton Helium Cycle.*

Fossil:
- *Open-System Brayton Air Cycle.*
- *Closed-System Rankine Steam Cycle*

US Patents: 7,961,835; 8,537,961

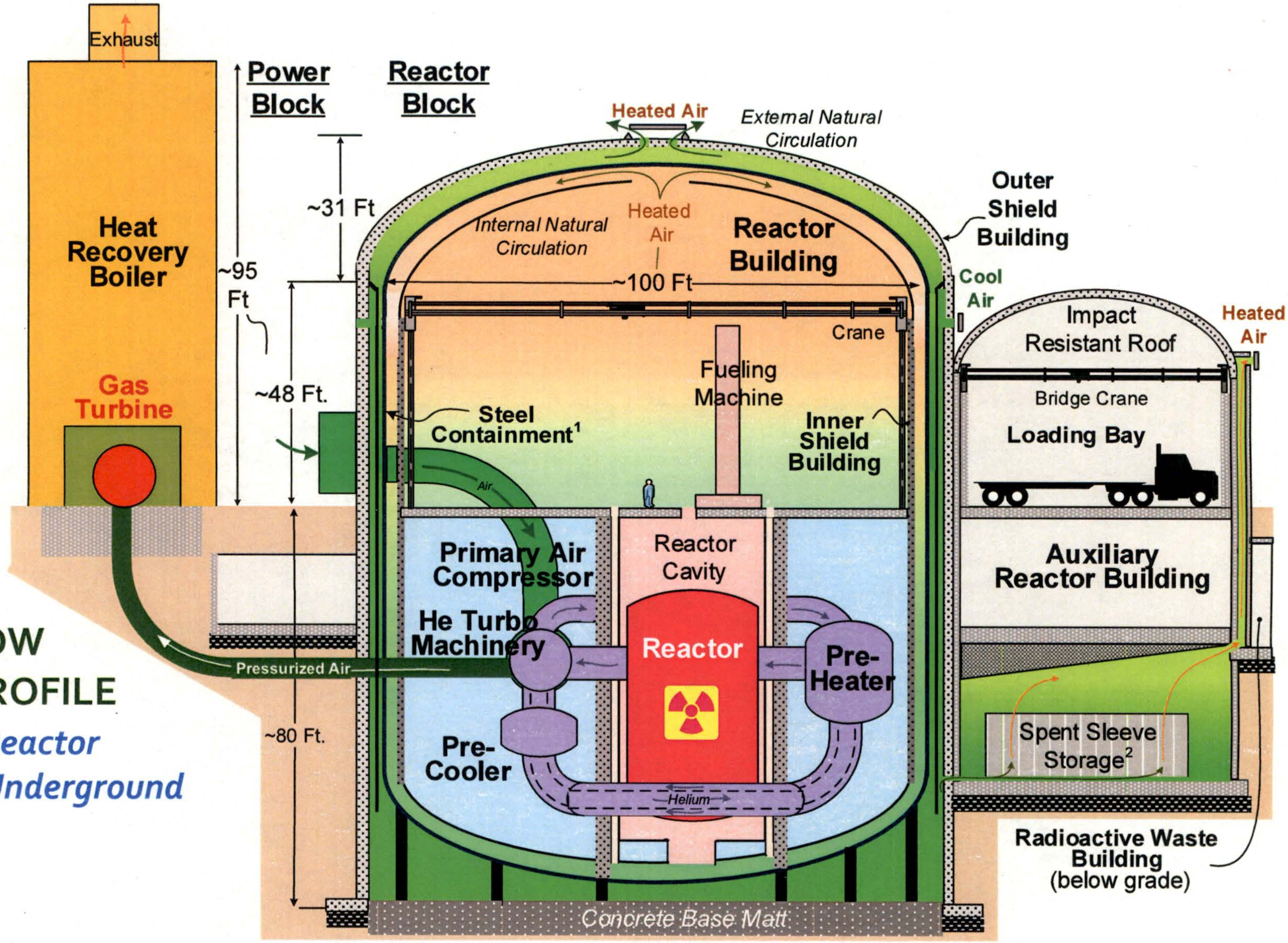
HYBRID/ All-Nuclear



HP = High Pressure
IP = Intermediate Pressure
LP = Low Pressure

CONCEPT

TECHNICAL: *Elevation*



➢LOW PROFILE

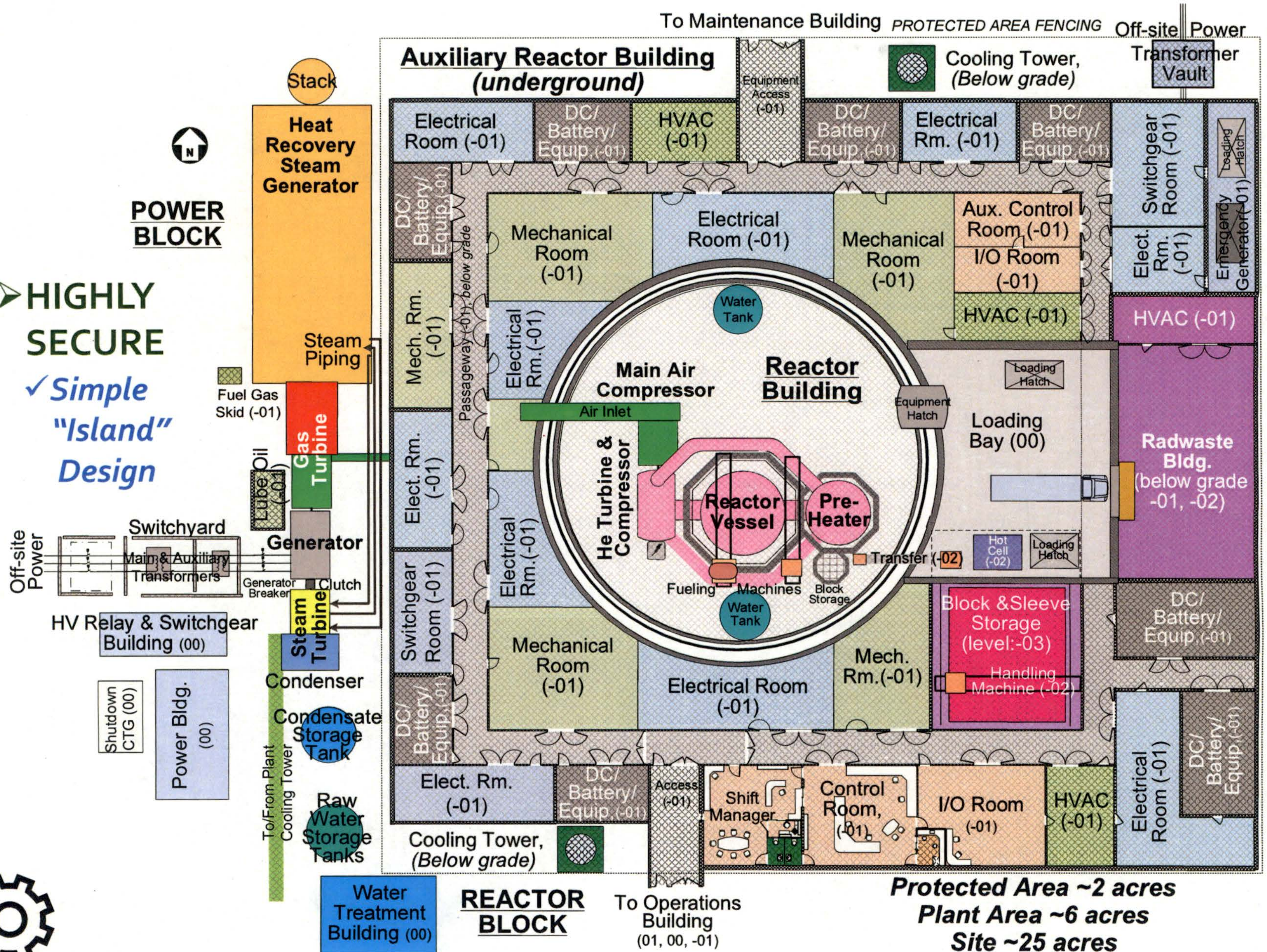
✓*Reactor Underground*

CONCEPT

<u>Notes</u>: *(1) ASME Section III, Subsection NE, Class MC Component. (2) See chapter End-notes, item H.*

TECHNICAL: *Plan View*

- ➤ **HIGHLY SECURE**
  - ✓ *Simple "Island" Design*

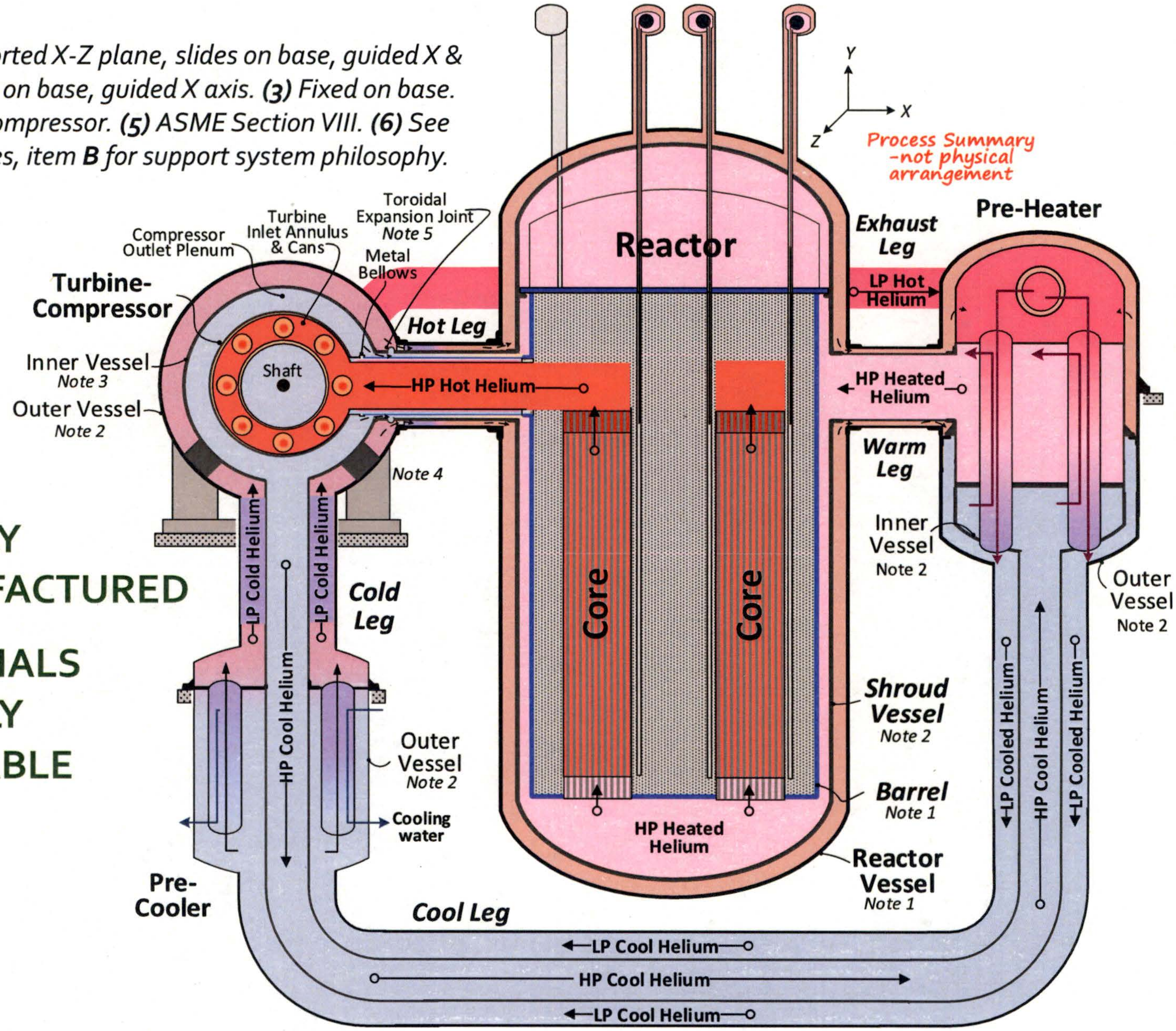


Protected Area ~2 acres
Plant Area ~6 acres
Site ~25 acres

CONCEPT

TECHNICAL: *Reactor System*

Notes: *(1) Supported X-Z plane, slides on base, guided X & Z axes. (2) Slides on base, guided X axis. (3) Fixed on base. (4) Cooling, He compressor. (5) ASME Section VIII. (6) See chapter End-notes, item **B** for support system philosophy.*



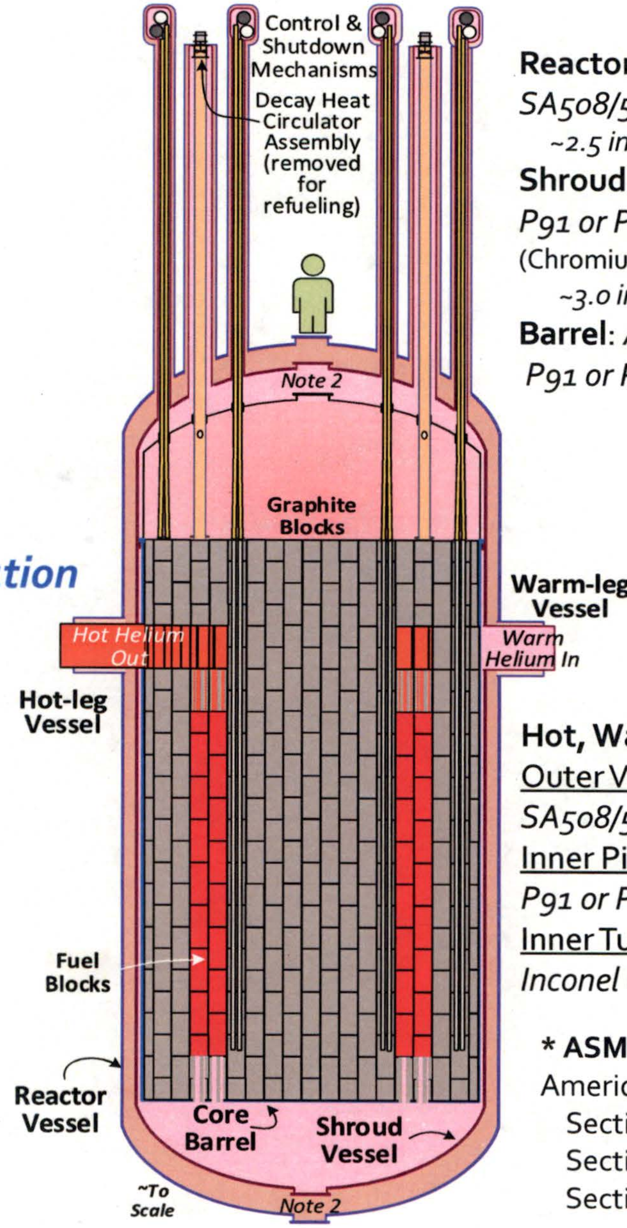
➢READILY MANUFACTURED

➢MATERIALS READILY AVAILABLE

CONCEPT

TECHNICAL: *Vessels*

- **SIMPLE APPROACH**
  - ✓ *Vessel-in-Vessel*
- **VESSELS & PIPING MEET ASME CODE***
  - ✓ *Design, Materials, Manufacture & Installation*
- **WELDED ROLLED PLATE**
  - ✓ *Readily Fabricated in North America*[3]



Reactor Vessel: *ASME Section III*
SA508/533 Carbon Steel Alloy,
~2.5 inches/65 mm thick
Shroud Vessel: *ASME Section VIII*
P91 or P92 Ferritic Steel[1]
(Chromium- Molybdenum Steel Alloy)
~3.0 inches/ 90 mm thick
Barrel: *ASME Section III*
P91 or P92

Hot, Warm, Cold &Turbine Exhaust Legs:
<u>Outer Vessels</u> *ASME Section III*
SA508/533 (Carbon Steel Alloy)
<u>Inner Pipe</u> *ASME Section VIII*
P91 or P92
<u>Inner Tubing & Metal Bellows</u> *ASME Section VIII*
Inconel 625 (Nickel Alloy)

*** ASME:**
American Society of Mechanical Engineers:
Section II -Materials
Section III – Nuclear Facility Components
Section VIII – Pressure Vessels

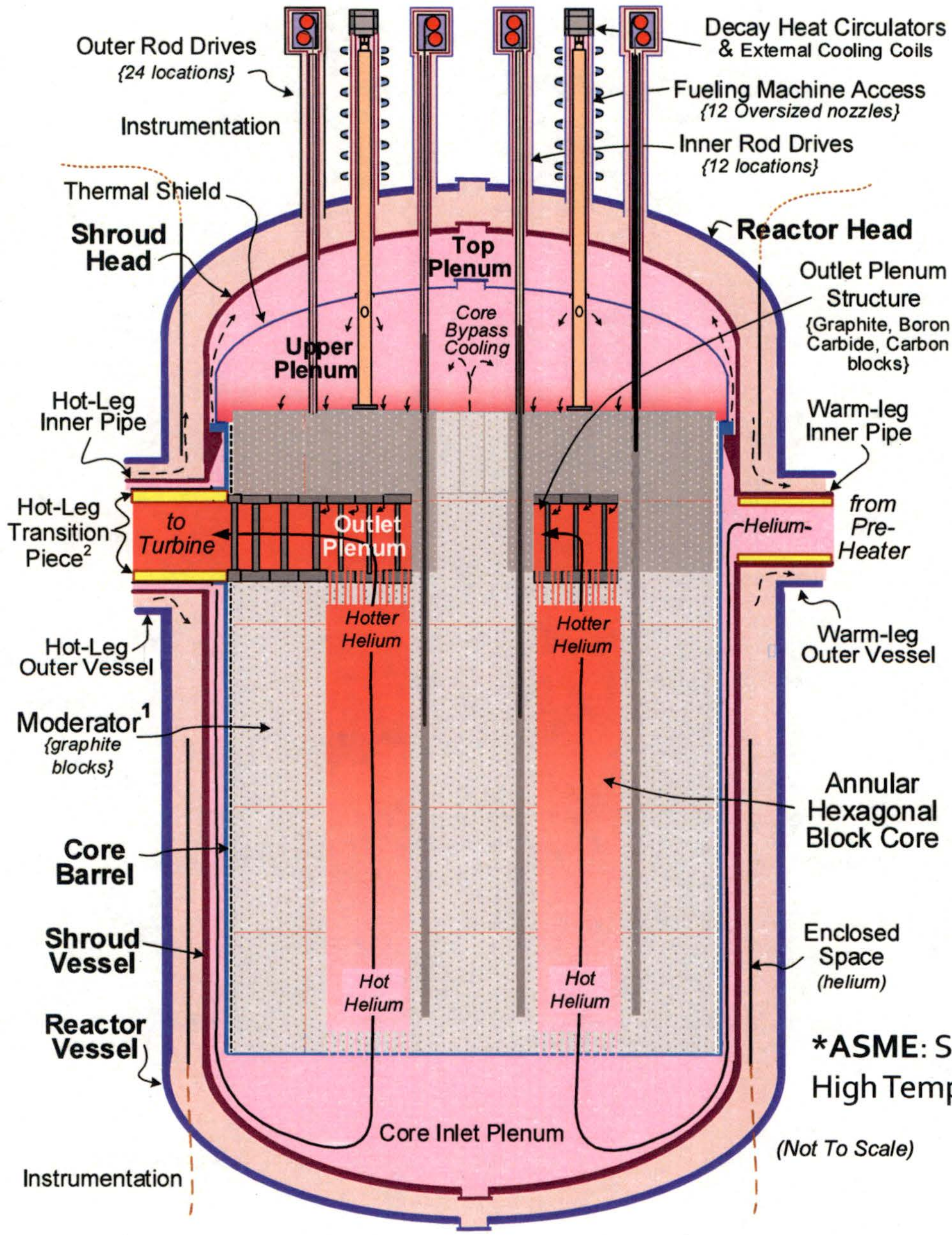
CONCEPT

 Rev. A

TECHNICAL: *Reactor*

➢CORE MEETS ASME CODE*

✓*Design, Materials, Manufacture, & Installation*



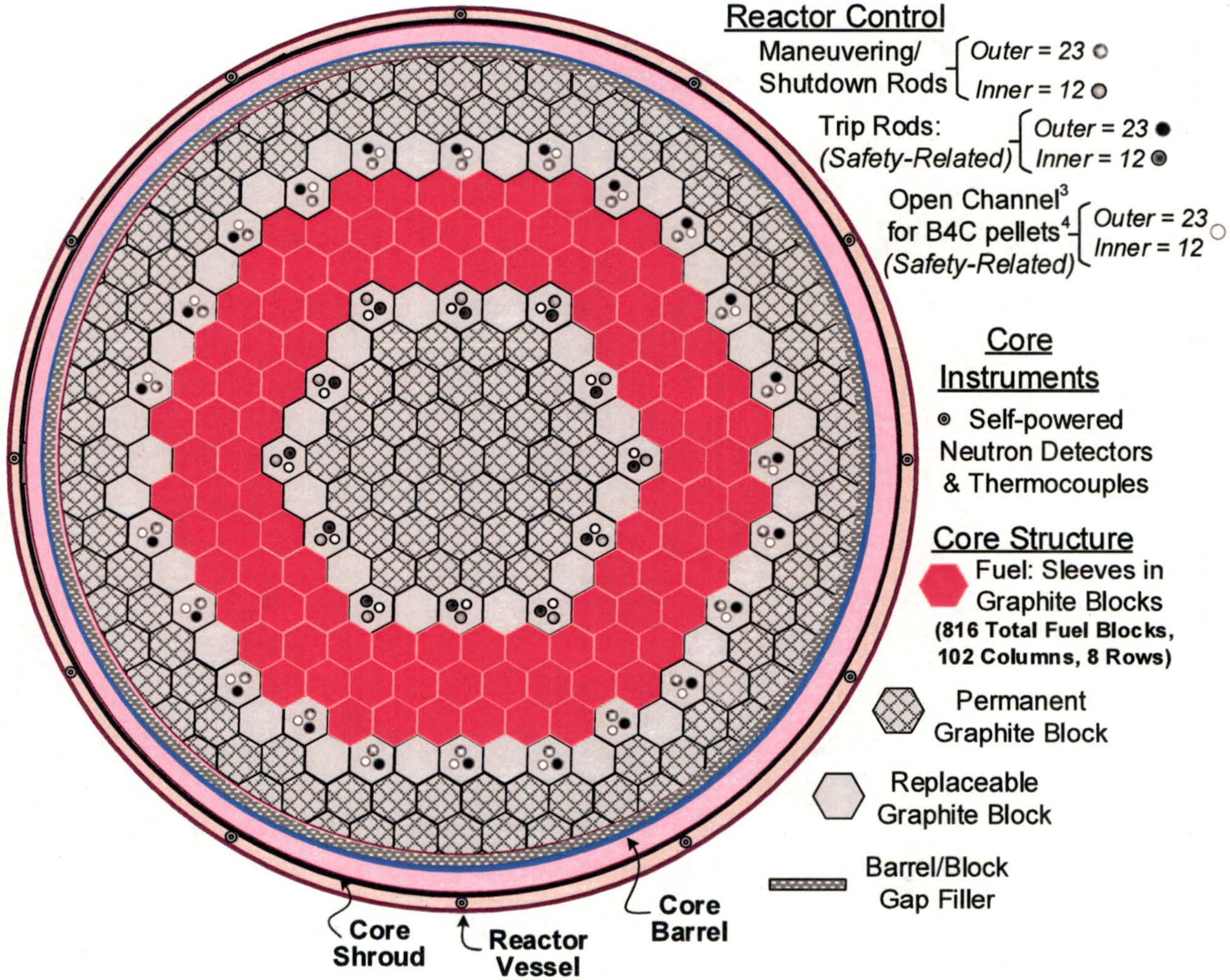
__Notes:__ ***(1)*** *Core laterally restrained by flexible bracing surrounding periphery of reflector blocks, with gap between core barrel & blocks filled with B_4C, carbon & graphite shapes for purposes of: neutron reflector, radiation shielding; insulation.. Avoids expensive machining of barrel inside diameter.* ***(2)*** *Internally insulated & cooled overlapping annular cans attached to cooled pipe/tube.* ***Proprietary*** *design*

***ASME**: Section III, Division 5 - High Temperature Gas Reactors

CONCEPT

TECHNICAL: *Reactor*

- **RUGGED & SIMPLE**
  - ✓ *Readily Refueled*
    - Shuffle Blocks and/or Sleeves[2]
- **Control Rod Pairs[1]**
  - ✓ *Trip & Maneuvering*
    - Safety & Control Functions Completely Separated
- **Instrumented**
  - ✓ *Pressure*
  - ✓ *Thermocouples*
  - ✓ *Neutron Detectors*



<u>Notes:</u> ***(1)*** *Control rod spacing roughly several times the neutron diffusion length (L). Water reactor, L ~ 2.8 cm. Graphite gas reactor, L ~54 cm.* **Ref. 28**. ***(2)*** *See chapter-Endnotes, item* ***J***. ***(3)*** *Also provides for cooling of control rod block* ***(4)*** *Pellets consist of B_4C particles in carbon matrix coated by ZrC to protect against corrosion and mechanical damage.*

CONCEPT

TECHNICAL: *Fuel*[1]

➢PROVEN

- ✓ *+ 50 Year History*
- ✓ *Periphery Cooled (Japan)*
  + Central Cooling (Hybrid)

➢MINIMAL to NO-LEAKAGE

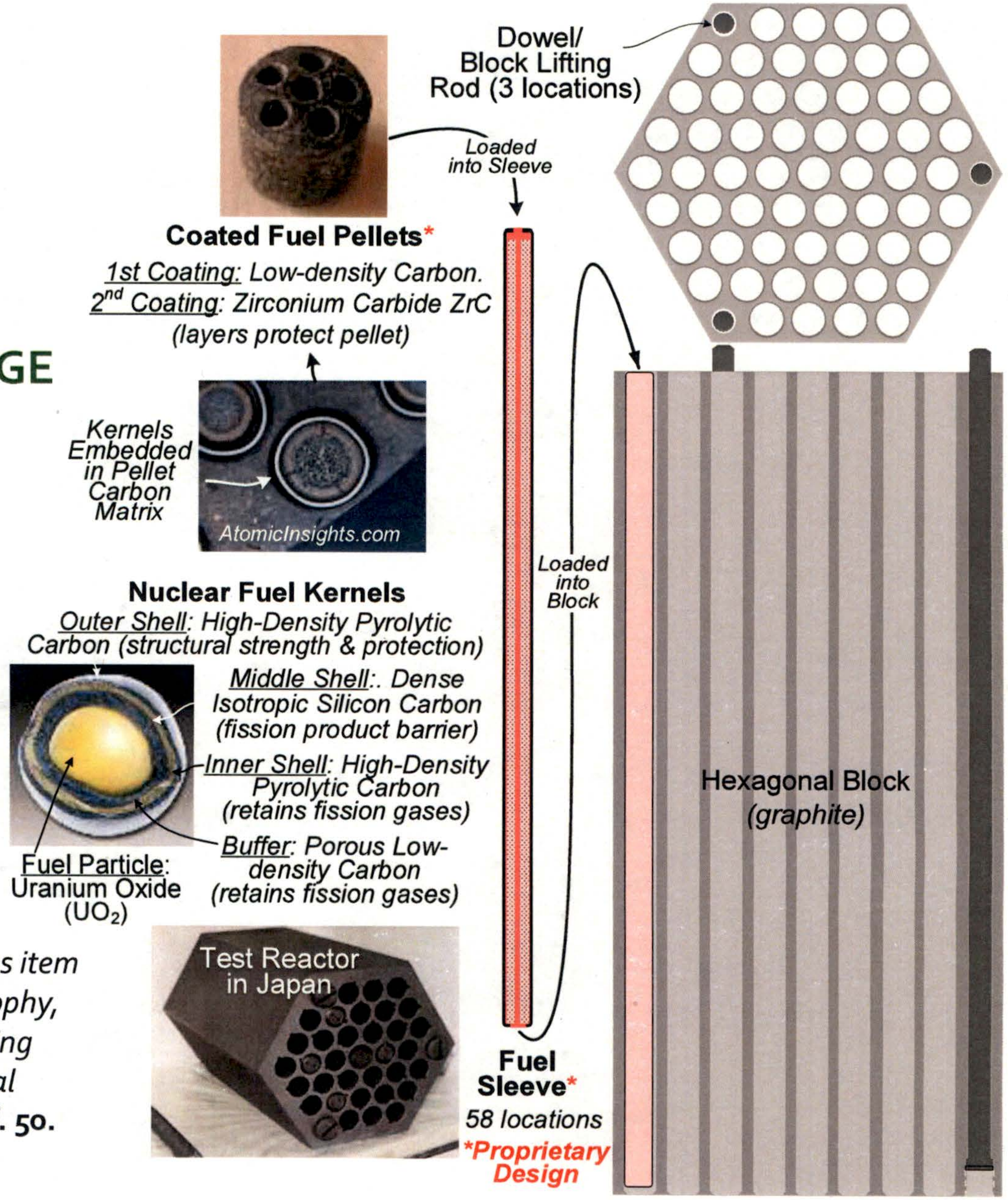
- ✓ *Coatings & Temperature*

➢REASONABLE COST

- ✓ *Readily Manufactured*

➢VERY ADAPTABLE

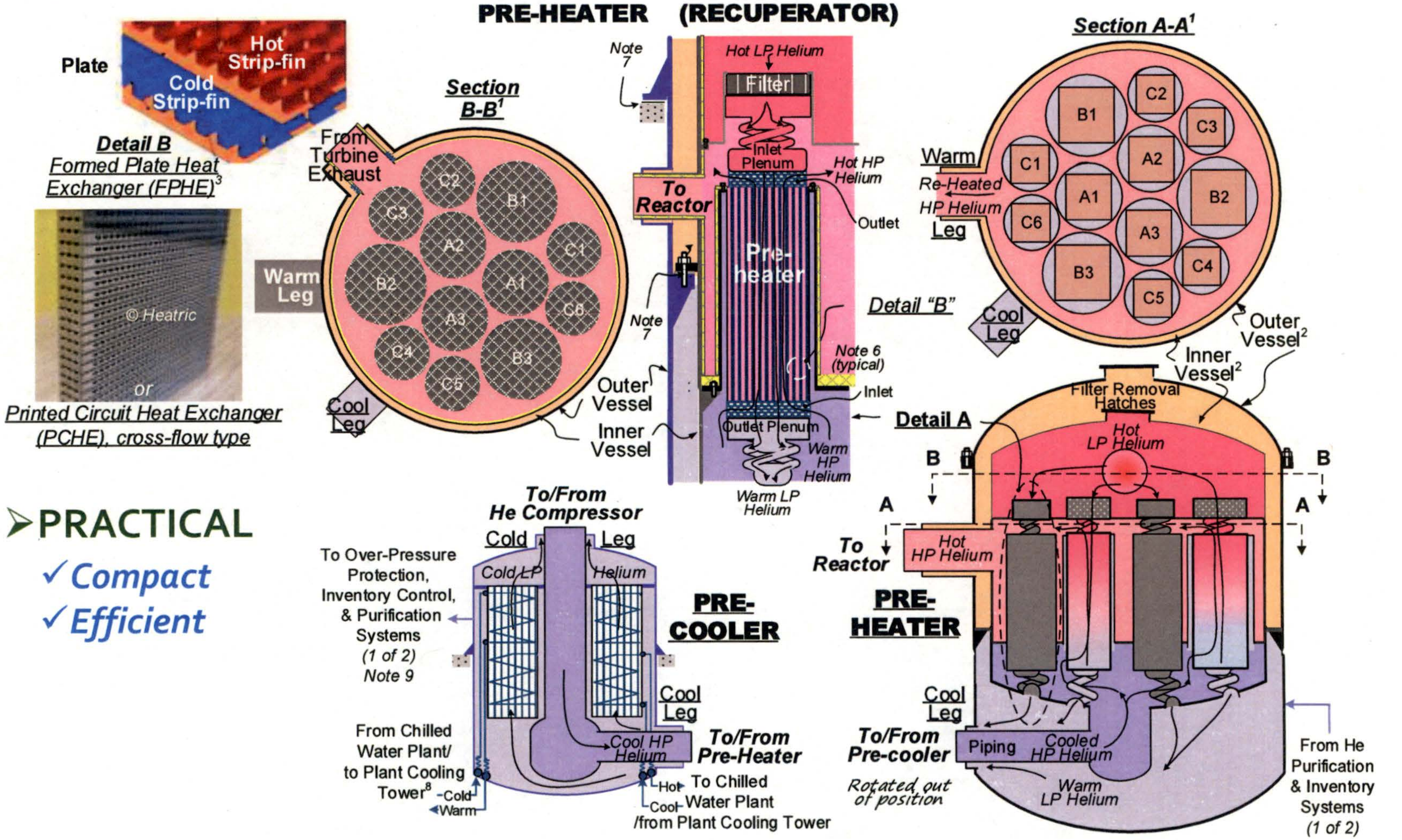
- ✓ *Uranium*
- ✓ *Mixed Oxide*
- ✓ *Plutonium*
- ✓ *Thorium*



Note: *(1) See chapter End notes item **D** for fuel general design philosophy, characteristics and manufacturing methods. Fissions in heavy Metal Atoms (FIMA) roughly 10%,* **Ref. 50.**

CONCEPT

TECHNICAL: *Heat Exchangers*



➢PRACTICAL

✓*Compact*

✓*Efficient*

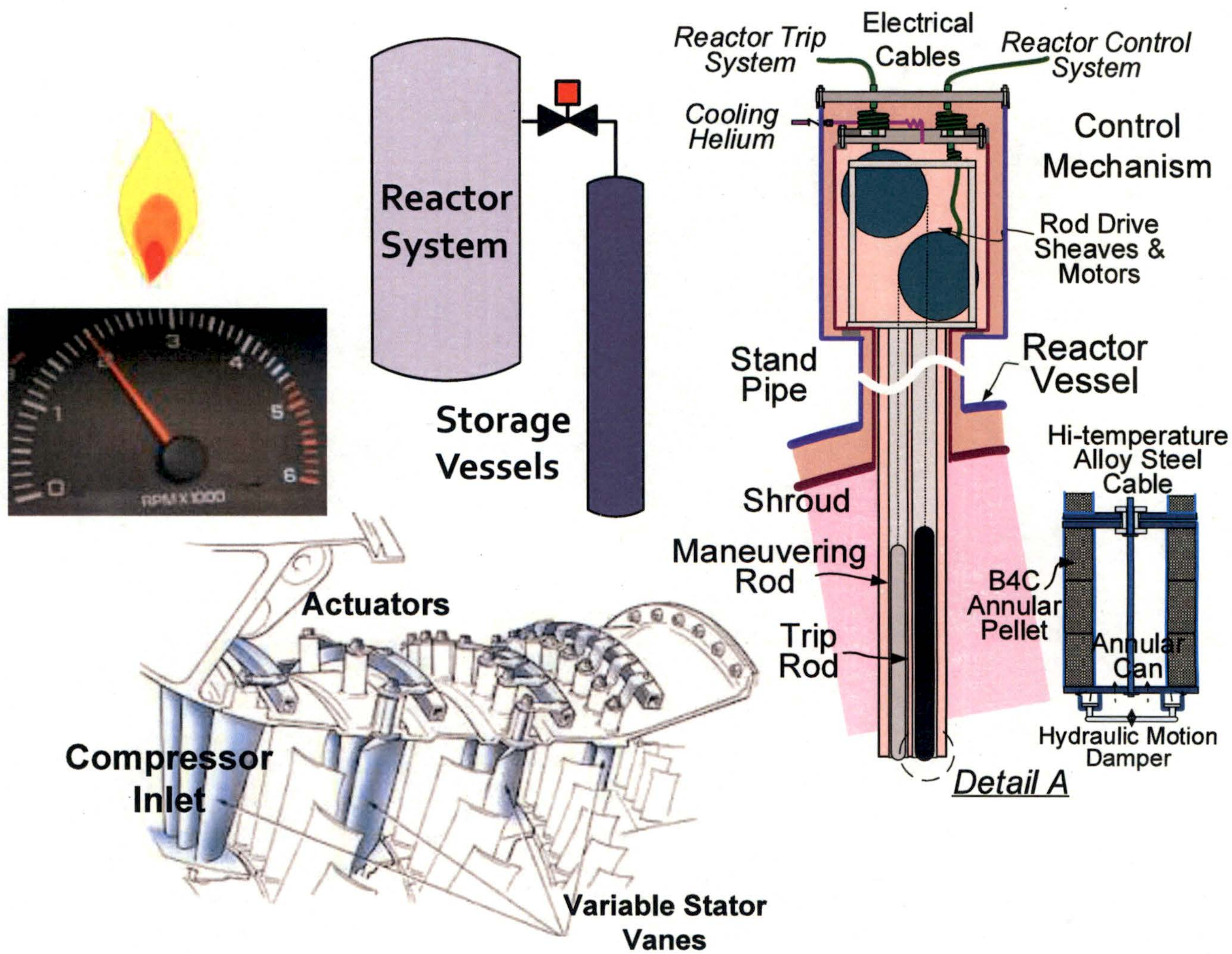
Notes: *(1) Optimum packing inside circle using conformal mapping. (2) Inner Vessel & Heat Exchangers ASME Section VIII, Outer Vessel Section III. (3) Diffusion bonded strip fins. FPHE exterior under high-pressure to insure bonding reliability. (4) Cooled meta/ bellows to accommodate thermal expansion of inner pipe. (5) Sintered metal filters see Chapter End-notes, item **M**. (6) Metal canned insulation. (7) Slides on base. (8) Can be supplied by Reactor Block Coolers during abnormal or emergency events (9) See* **TECHNICAL** *Endnotes, item **M**.*

CONCEPT

TECHNICAL: *Control*

➢ **FLEXIBLE & EFFICIENT**

- ✓ *Combustion Turbine Firing Temperature[1] (fuel flow)*
- ✓ *Primary Compressor Air Flow[1]*
- ✓ *Compressor Helium Flow[1]*
- ✓ *Control Rods/ Core Power[2]*
- ✓ *Helium Inventory[2]*



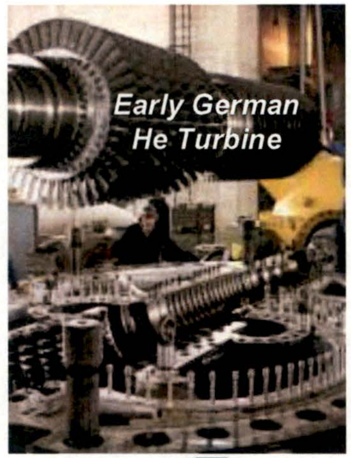
Notes: ***(1)*** *Rapid load following: gas turbine inlet stator vanes; firing temperature; helium turbine & compressor bypass.* ***(2)*** *Intermediate & daily load following: He inventory; reactor temperature (via maneuvering rods); turbo-machinery speeds.* ***(3)*** *Trip rods are not located in core during power operation.*

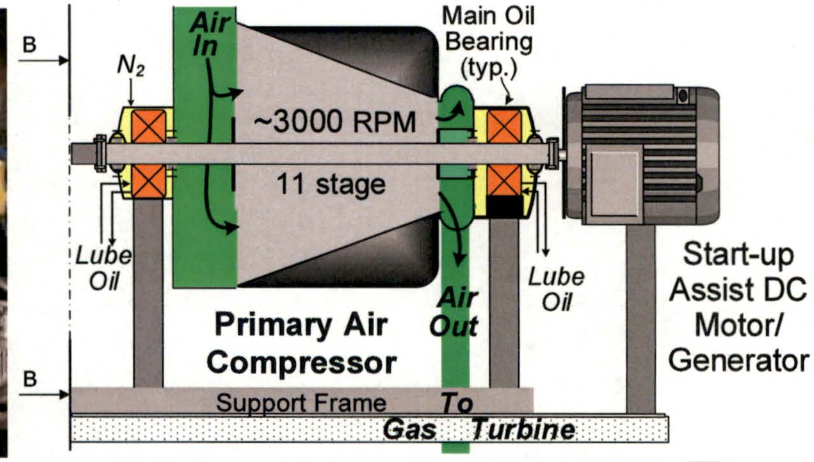
CONCEPT

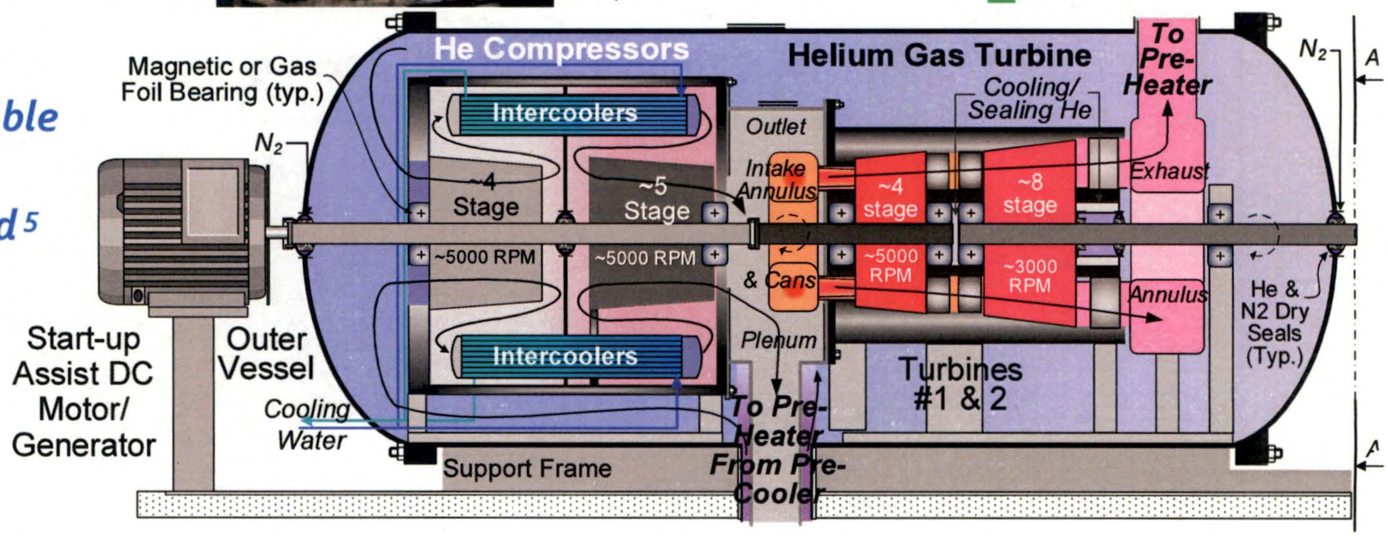
TECHNICAL: *He Turbine-Compressor*

➢PRACTICAL APPROACH[1]

- ✓*He Turbines Viable*[7]
- ✓*Horizontal Machine*
- ✓*Materials Readily Available*
- ✓*Efficient & Maneuverable*
- ✓*Readily Overhauled*[5]





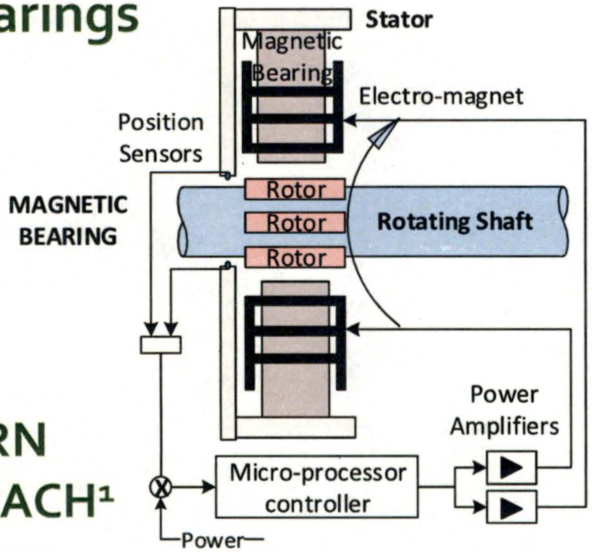


Notes: (1) See chapter End-notes, item **A**. *(2) Speeds estimated using* **Ref. 8**. *He Turbine #1 configured for optimized He compressor. He Turbine #2 configured for optimized Primary Air Compressor.* **(3)** *Motor/generators feed bus providing power to magnetic bearings. Eddy current brakes employed with motor/generators to mitigate over-speed conditions.* **(4)** *See chapter End- notes, item* **F**. **(5)** *See chapter End-notes, item* **G**. **(6)** *"Can" design between inlet annulus and turbine inlet stator is* ***Proprietary***. **(7)** *See chapter End- notes, item* **L**.

CONCEPT

TECHNICAL: *He Turbine-Compressor*

/Oil-Free Bearings

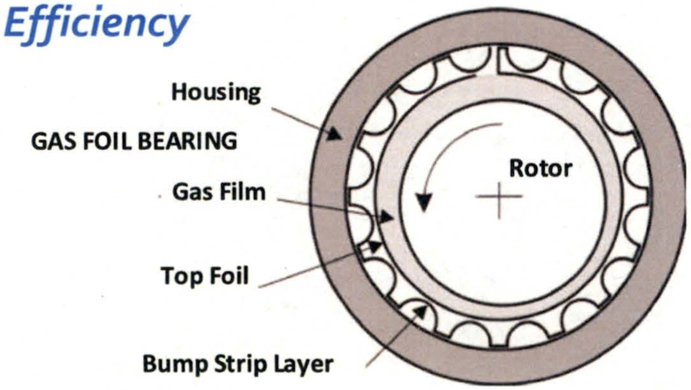


Active magnetic bearing consists of stationary stator, containing electromagnets, position sensors, and the rotors that rotate with the shaft. When the bearing operating, each rotor is ideally centered in corresponding stator so that contact does not occur. Shaft radial position controlled using a closed-loop feedback system. Position sensors detect the local shaft displacements and signals are sent to a digital controller.

Although not shown, axial magnetic bearings are also employed. Axial control adjustments optimize performance of the seals used to minimize helium leakage from the ends of the rotating shaft Control system calculates re-distributes electro-magnet currents to restore shaft to centered position. Power amplifiers readjust the electromagnet currents according to these calculations. Cycle typically repeated approximately 15,000 times per second.

➢ **MODERN APPROACH[1]**

✓ *Enhances Efficiency*



Foil bearings, also known as gas foil bearings, carry a load on a thin film based on the principal of hydrodynamic pressure. Advantages include: low maintenance& high reliability; zero contamination; wide temperature range, up to ~650OC; high speed operation. A Sommerfeld number (S) greater than 6 means machinery is a good candidate for foil bearings – Ref. 60

S = (r/c)^2 *μ *N/P

- r = Shaft Radius
- c = radial clearance
- μ = Absolute Viscosity of gas
- N = Shaft speed, revolutions/second
- P = Load per unit of bearing area.

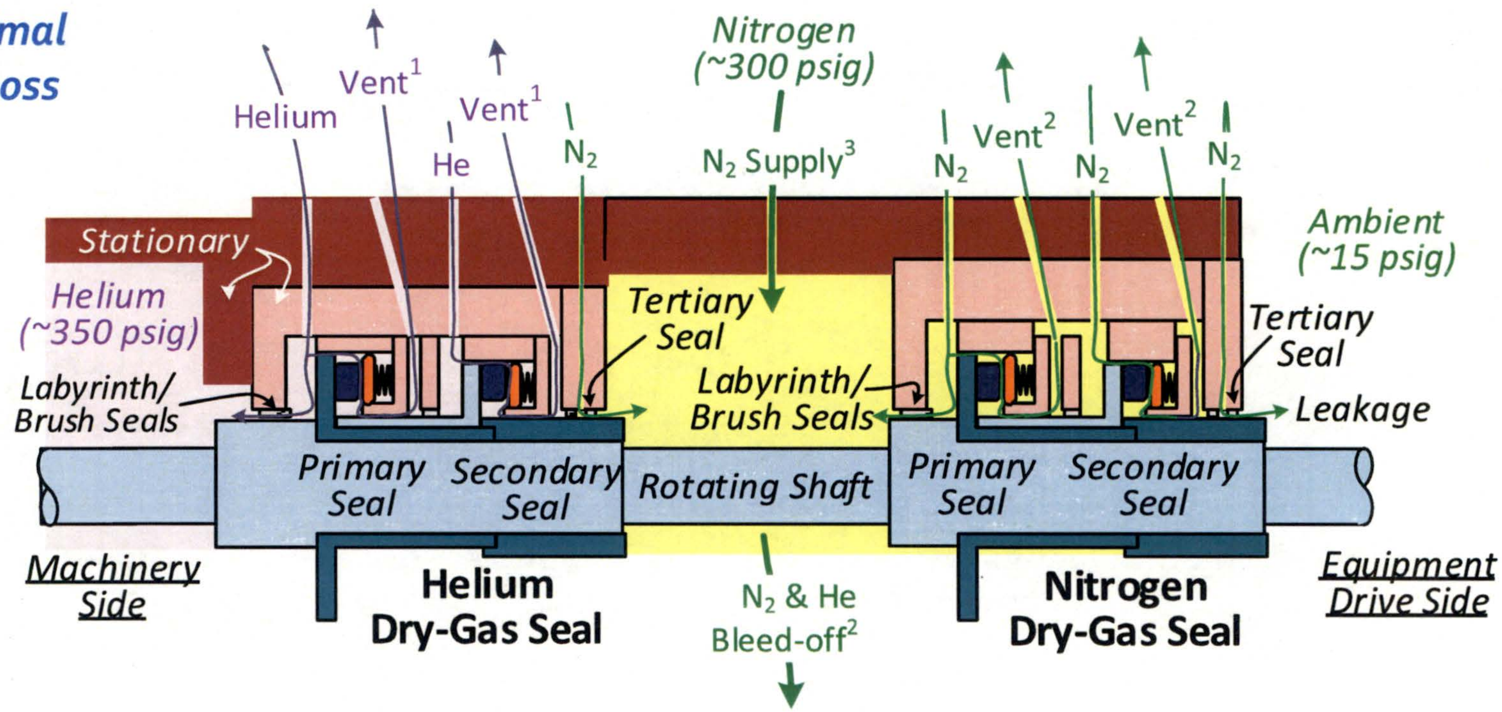
The gas foil bearing is preferred over a magnetic bearing from a cost standpoint.

<u>Note</u>*: **(1)** Magnetic bearings are increasingly being used on large turbines and compressors. However, the reliability of these bearings in nuclear applications may not be fully sufficient. An alternative approach is a single shaft configuration with highly reliable conventional oil bearings used on the shaft ends. However, drawbacks include several percent reduction in machine output and efficiency; oil contamination of reactor*

CONCEPT

TECHNICAL: *He Turbine-Compressor*
/Shaft Sealing

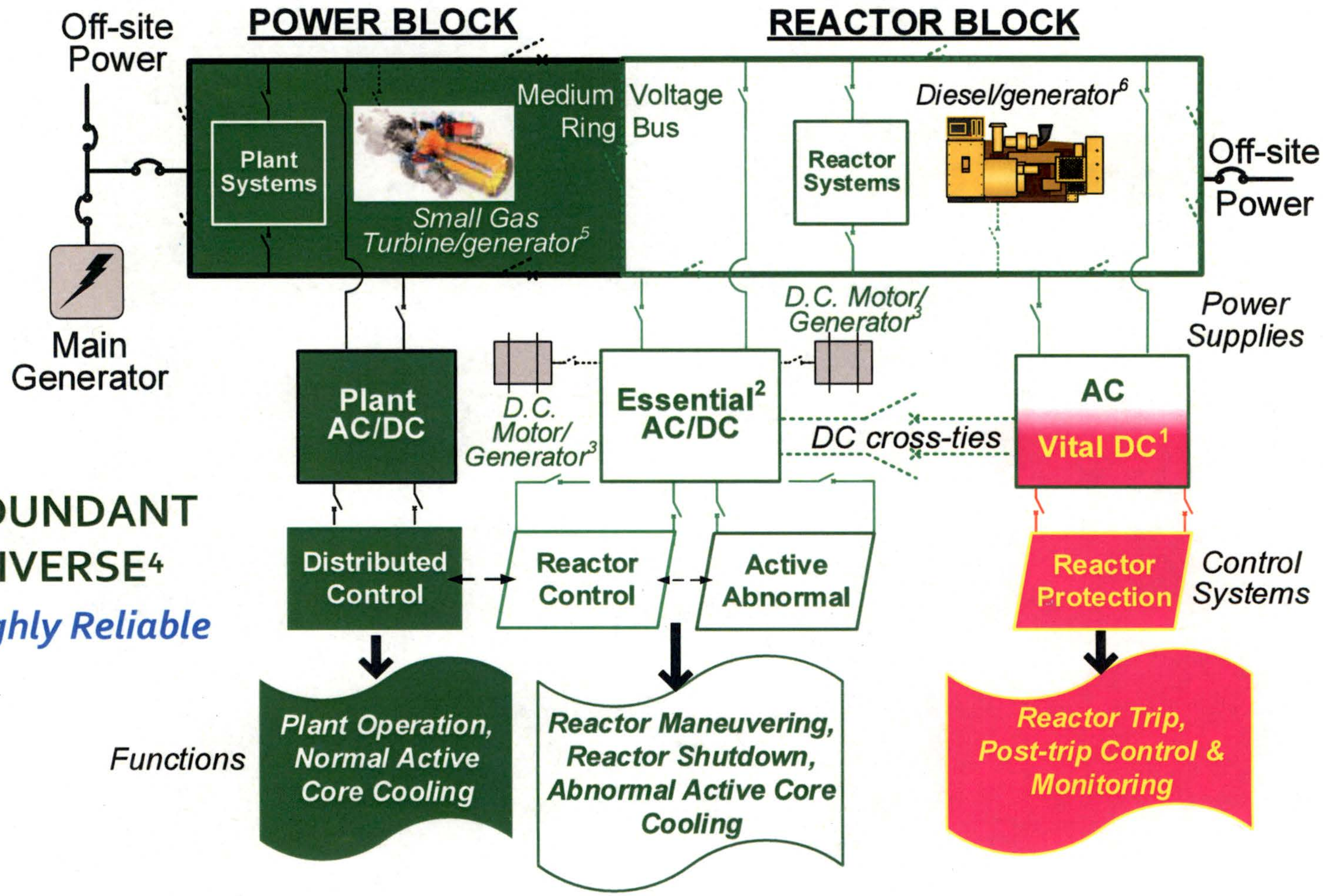
- **MODERN GAS TURBINE TECHNOLOGY**
  - ✓ *Minimal He Loss*



Notes: ***(1)*** *To He hold-up tanks for recycle.* ***(2)*** *To filters & Molecular Sieve for He & N2 clean-up & separation, then to hold-up tanks for recycle.*

CONCEPT

TECHNICAL: *Electrical & Control*



➢**REDUNDANT & DIVERSE**[4]

✓*Highly Reliable*

Notes: **(1)** Vital *Power supply = Safety-related DC,* **(2)** *Essential = Supplemental Safety.* **(3)** *Driven by Helium turbines.* **(4)** *Control features completely separated from safety-related control systems (Reactor Trip).* **(5)** *Emergency power, fired by diesel fuel or natural gas.* **(6)** *Emergency power, fired by diesel.* **(7)** *Medium voltage ring bus cables located in buried concrete boxes located above underground auxiliary reactor building to mitigate fire issues and simplify construction.*

CONCEPT

TECHNICAL: *Readiness*

➢GOOD

- ✓ ***Adapts Proven Equipment***
- ✓ ***Development, Not Research***

Key Components	Design	Manufacturers
Vessels	✓	✓
Nuclear Fuel[1]	*	✓
Gas Turbine & Compressor[2]	*	✓
He Turbine & Compressor[2]	*	✓
Steam Turbine	✓	✓
Heat Exchangers	✓	✓
Heat Recovery Boiler	✓	✓
PROTOTYPE[4]	✓	✓

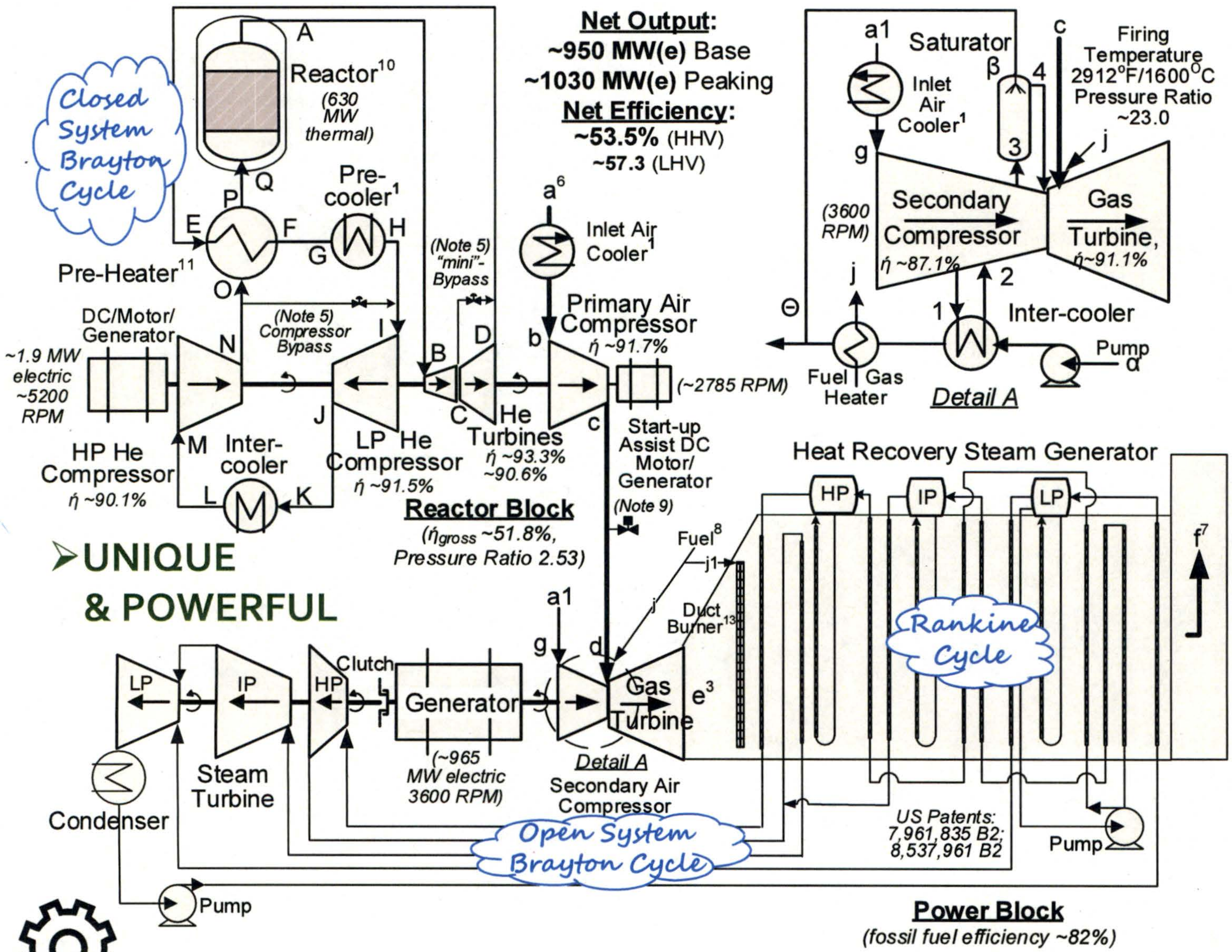
✓ = ***Available*** * = ***Some Development Effort*** # = ***Long-range effort***

Notes: **(1)** *Hybrid **proprietary** design requires initial development testing, e.g. at US DOE laboratories. Testing of production fuel bocks envisioned to occur at existing High Temperature Test Reactor (HTTR) located in Japan.* **(2)** Gas *turbine/compressor initial testing can occur at manufacturer facilities. GE facility uses compressor as load (in lieu of generator) which also allows for testing helium machines -* **Ref. 23.** ***(3)*** *Advanced Hybrid cycle, can be tested with conventional advanced gas turbine combined-cycle plant.* ***(4)*** *Hybrid/All-nuclear used for integrated reactor testing. Power block does not require prototype testing as technology is considered well developed.*

CONCEPT

TECHNICAL: *Thermal Cycle*

Today's Technology



Notes:

(1) *Reactor Block pre-cooler waste heat used with absorption chillers to cool turbine inlet air and pre-cooler.*

(2) *Ambient: 59°F; 60% Humidity; Sea Level*

(3) *Exhaust ~1191F/644°C, ~1695 Lbm/s.*

(4) *Machine efficiencies based on work weighted average of stages.*

(5) *Bypass for control purposes.*

(6) *Inlet losses ~8" H_2O.*

(7) *Outlet losses ~15" H_2O. Temperature ~215°F*

(8) *Natural Gas ~49.6lbm/s or Coal Gas.*

(9) *Gas Turbine Bypass.*

(10) *Helium ~818 lbm/s, Tin~857°F/458°C, Tout~1445 °F/785°C*

(11) *Efficiency η_{HtEx} ~94.5%.*

(12) *Turbo-machinery polytrophic efficiency.*

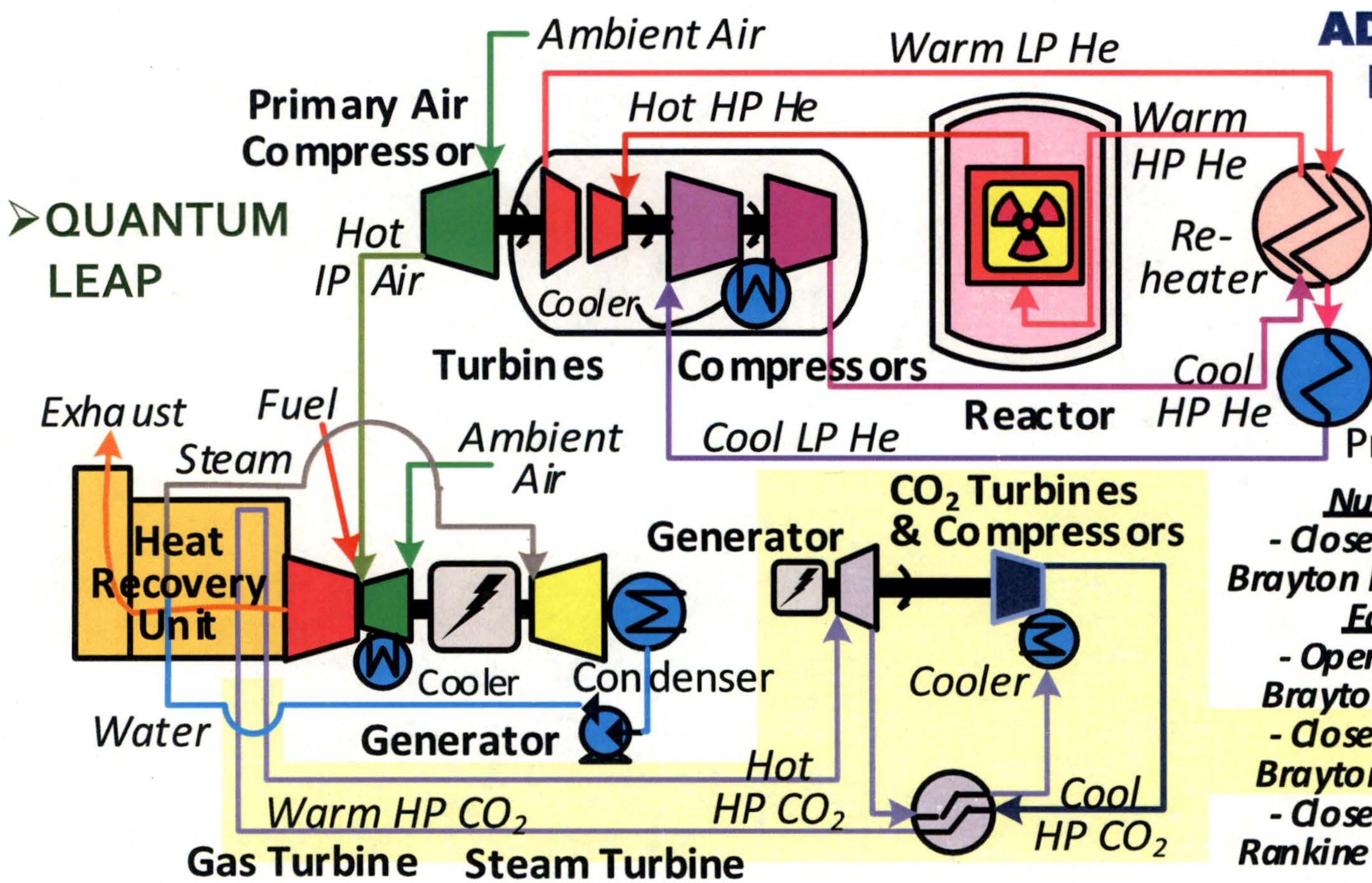
(13) *Peaking Operations. Duct burners are capable nearly doubling steam turbine output – maximum peaking of over ~1100 MW(e) possible.*

CONCEPT

TECHNICAL: *Advanced Thermal Cycle*

Hybrid-Nuclear Energy

Long Range



Nuclear:
- Closed-System Brayton Helium Cycle.

Fossil:
- Open-System Brayton Air Cycle.
- Closed-System Brayton CO_2 Cycle.
- Closed-System Rankine Steam Cycle

HP, IP, LP = High. Intermediate & Low Pressure

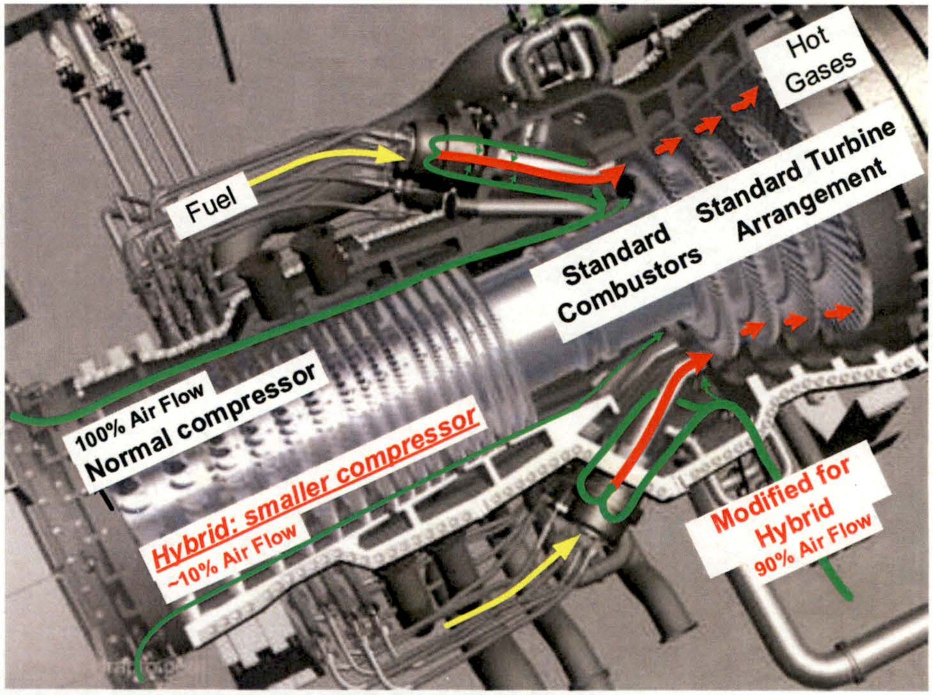
CONCEPT

TECHNICAL: *Contrast*

/Gas Turbine

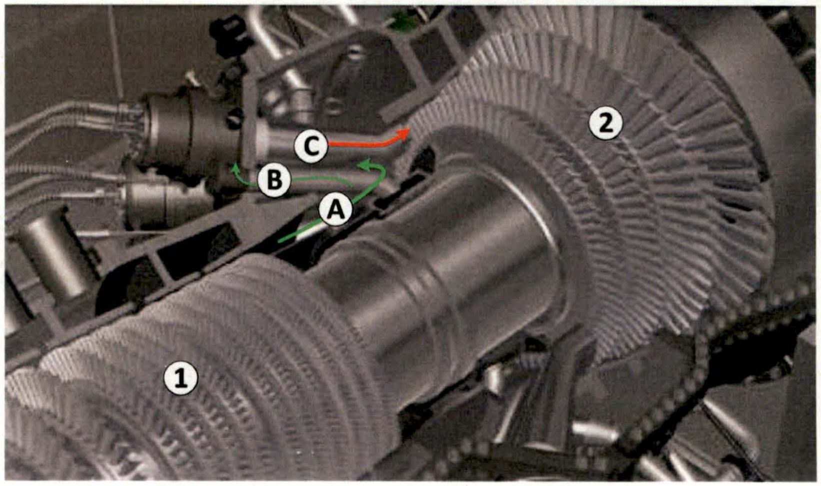
	HYBRID	*Conventional*
Efficiency[1]	+65 %	~41.5 %
Heat Rate (BTU/kWh)	~5075	~8220
Output	~X 2.2	1.0

Note: (1) *Fossil fuel use.*



➢ **ADAPTS & ADVANCES PROVEN DESIGNS**

✓ *Larger Electrical Output & More Efficient Fuel Use*



1. Compressor Blades.
2. Turbine Blades.

A. Primary Air Flow.
B. Transition Piece Cooling.
C. Turbine Inlet Hot Gas.

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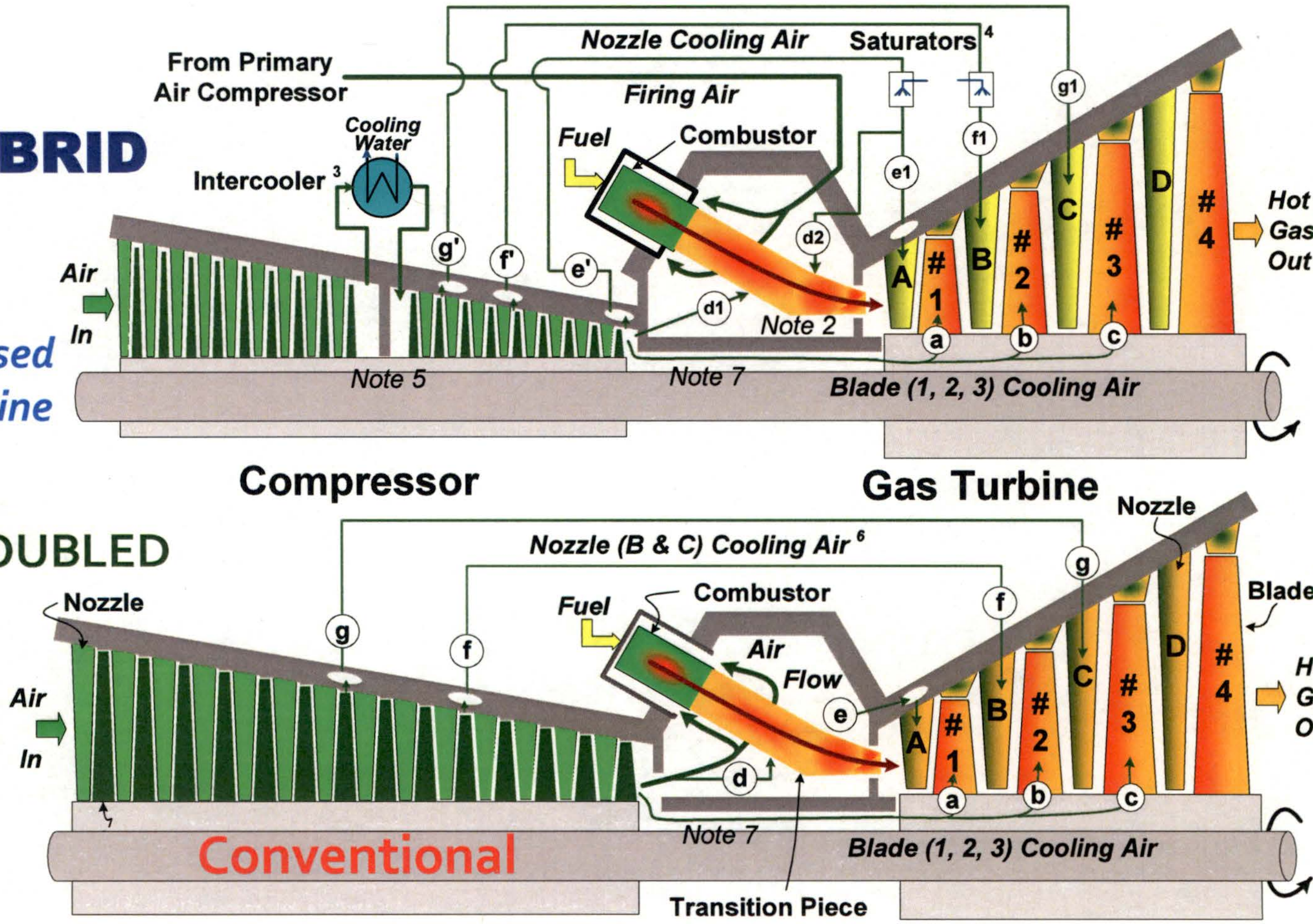
CONCEPT

TECHNICAL: *Contrast*

/Gas Turbine[1]

HYBRID

- **MORE EFFICIENT**
  - ✓ *Less Power Used Cooling Machine*
- **ELECTRICAL OUTPUT ~DOUBLED**
- **BETTER COOLING**
  - ✓ *~ 50% Colder Air*



<u>Notes</u>: **(1)** Major improvement, see Chapter end-notes, item **A**. ***(2)*** *Concept somewhat similar to MHI 701J experimental use of external "boost-up" compressor to achieve 3000°F/1650°C firing temperatures -* **REF. 62.** *Expectation is Hybrid will readily achieve this target with net output of ~1025 mW (e).* ***(3)*** *Similar to GE LMS 100 compressor.* ***(4)*** *Cools by evaporating water.* ***(5)*** *~ 20 stages.* ***(6)*** *Too hot for saturator use.* ***(7)*** *Cooler (or saturator in case of hybrid) used to reduce blade cooling air temperature.*

CONCEPT

TECHNICAL: *Contrast*
/Nuclear Plants

➢HYBRID
VERY
GOOD
POWER
PLANT
✓*Ideal for Today's Grid*

NAME	HYBRID	*GTHTR300*[2]	*AP 1000*[3]	*NUSCALE*[4]
Origin	US	Japan	US	US
Status	Concept Design	Design	Operating[5]	Design
Plant Output mW Electric	Large +950	Moderate ~279	Large ~1115	Small to Moderate ~540, 45X 12
Site Area, acres	~20	~75 (estimated)	~750 (estimated)	~520
Units or Modules	1	1	1	12
Staff	Small <100	Small Est. ~125	Very Large Est. ~700	Moderate Est. ~400
Cycle Type	Brayton (Nuclear) / Brayton/ Rankine (fossil)	Brayton (Gas)	Rankine (Steam)	Rankine (Steam)
Efficiency	~50% / ~80%	~45%	~34%	~28%

Notes: **(1)** *Developed by US small business, Hybrid Power Technologies LLC.* **(2)** *Operational High Temperature Test Reactor (HTTR) serves as prototype for GTHTR (Gas Turbine High Temperature Reactor)* - **Ref. 1**. *Hybrid is somewhat similar to Japanese designs.* **(3)** *Westinghouse (formerly owned by Toshiba of Japan, 2017) pressurized water reactor,* **Ref. 2.** **(4)** *Pressurized water reactor, NUSCALE owned by US company Flour,* **Ref.44.** **(5)** *China.*

CONCEPT

TECHNICAL: *Contrast*

/Reactors

➢ HYBRID SIMPLE

✓ *Readily Designed & Manufactured*

✓ *History's Lessons Learned*[4]

NAME	HYBRID	GTHTR 300	AP 1000	NUSCALE
Reactor Type	Gas	Gas	Water	Water
Reactor Output mW thermal	Small ~630	Small ~600	Large ~3415	Very Small ~160 x 12
Coolant	Helium	Helium	Water	Water
Primary Driver	Helium Turbine[1]	Helium Turbine[2]	Pump	Natural Circulation
Moderator	Graphite	Graphite	Water	Water
Inlet Temperature °F/°C	~887/ 475	~1088/ 587	~525/ 280	~425/ 218
Outlet Temperature[1] °F/°C	~1445/ 785	~1562/ 850	~615/ 324	~590/ 310
Refueling, Months	<12 to 18[3]	24	24	24 to 48

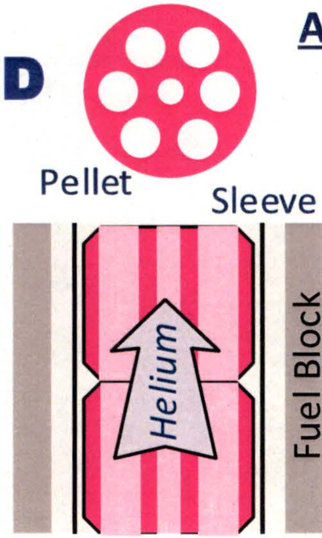
<u>Notes</u>: *(1) Helium turbine pressure ratio ~2.3.* ***(2)*** *Helium turbine pressure ratio ~1.87.* ***(3)*** *Shuffling of fuel or refueling can occur in spring or fall to optimize uranium utilization. Grid power needs typically reach minimum at these times, thereby readily supporting brief shutdown. The Hybrid is designed for rapid fueling operations which allows for optimizing even fuel burn up, thereby reducing fuel costs. From grid perspective, no particular need for extended years between refueling. (4) See* **Appendix D** *for summary of mitigation measures for operational issues involving earlier gas reactors.*

CONCEPT

TECHNICAL: *Contrast*

/Nuclear Fuel

HYBRID



Advanced Block & Sleeve[1]

- *Coated fuel pellets in several dozen sleeves in block holes.*
- *Outside & inside of sleeve & pellets cooled. (Proprietary Design)*
- *Blocks recycled for refueling after sleeve removal.*

➢ **MORE COST EFFECTIVE**

✓ ***More Reasonable Manufacturing Costs***

✓ ***More Reasonable Refueling Costs***

➢ **MINIMAL to NO RADIOACTIVE LEAKAGE**

✓ ***Much Lower Fuel Temperatures***

✓ ***Minimal or no Fuel Particle Failures***

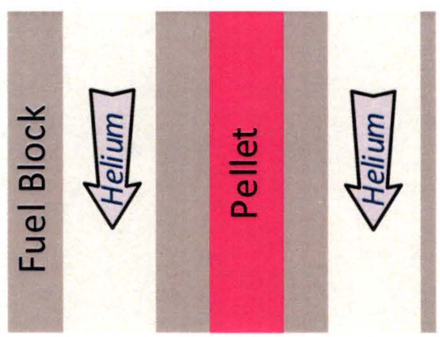
Conventional

Block & Sleeve

- *Fuel pellets in several dozen sleeves in block holes.*
- *Outside of sleeve cooled.*
- *Blocks replaced for refueling.*

Block & Pellet

- *Fuel pellets in block holes.*
- *Hundreds of holes for pellets & cooling.*
- *Blocks replaced for refueling.*



Conventional Gas Reactor

Note: **(1)** The Hybrid design is based on minimizing uneven pellet thermal gradients to avoid structural failures that could cause fuel kernel failure and subsequent fission product release. *See chapter End-notes, item* **D** for manufacturing approach.

CONCEPT

TECHNICAL: *Contrast*
/Nuclear Fuel

➢ HYBRID TOUGH & SAFE

✓ *Operates Well Below Limits*

NAME	HYBRID	GTHTR 300[4]	AP 1000[5]	NUSCALE[6]
Characteristics	☆ Si/C Coated UO_2 in Coated Carbon Pellet	Si/C Coated UO_2/UC in Carbon Pellet	UO_2 Pellets In Metal Tube	UO_2 Pellets In Metal Tube
Generation Burn-up[1], net electric gigawatt-days/ tonne Uranium	~105 x 150% ~157	~110 x 42% ~46	~50 x 32% ~16	~40 x 28% ~11
Fissions in Heavy Metal Atoms, FIMA[7]	~10%	☆ ~11%	~5%	~4%
Average Enrichment	~12%	~14%	<4.95%	☆ < 4.95%
Power Density[2] Watt/cm^3	☆ ~9	~10	~380	~180
Normal Peak Fuel Temperature, °F/°C	☆ <1880/ 1025	<2030/ 1110	<2745/ 1507	<2745/ 1507
Accident Peak Fuel Temperature, °F/°C	☆ <2200/ 1500	<2912/ 1600	<4500/ 2482	<4500/ 2482
Relative Spent Fuel [3]	☆ ~7%	~24%	~68%	100%

<u>Notes</u>*:* ***(1)*** *Average Burnup* (Electrical Output /Reactor Output).* ***(2)*** *Estimate based on (reactor power)/(core solid volume).* ***(3)*** *See chapter-Endnotes, item* ***I****.* ***(4)*** **Refs 1 & 50**. ***(6)*** **Ref. 2.** ***(7)*** **Ref 48.** ***(8)*** *Roughly, 1 FIMA ~ 97650 mW day/Ton U*

CONCEPT

TECHNICAL: *Rankings*
/Nuclear Plants

Category[1]	HYBRID	Water Reactors	Gas Reactors
Manufacturing Capability (US)	☆	✗	✗
Fabrication Ease	☆	✗	✗
Construction Ease	☆	✗	✓-
Operations Ease[2]	☆	✗	✓-
Efficiency	☆	✗	✗+
Output	✓+	☆	✗
Readiness	✗	☆	✓-
Future Potential[3]	☆	✗	✗+
NET[4]	✓+	✗+	✗+

☆ = *Best*, ✓ = *Average*, ✗ = *Needs Work.*

➤HYBRID BEST

✓ *Most Pragmatic*

Notes: *(1) Scoring relative to each other.* ***(2)*** *Ease of operating & repairing the power plant.* ***(3)*** *Output & efficiency improvement potential.* ***(4)*** *Average of Categories.*

CONCEPT

TECHNICAL: *Rankings*
/Power Plants

Category[1]	Gas	HYBRID	Coal	Wind & Solar	Nuclear
Manufacturing Capability (US)	★	★	★	✗+	✗
Fabrication Ease	✓	✓	✓-	★-	✗
Construction Ease	✓	✓-	✗+	★	✗
Operations Ease[2]	★	✓+	✗+	✓-	✗
Efficiency	✓	★	✗+	✗	✗+
Output	✓-	✓+	✓+	✗	★
Readiness	★	✗	★	★	★
Future Potential[3]	✓+	★	✗+	✗+	✗
NET[4]	✓+	✓+	✓	✓	✗+

★ = *Best*, ✓ = *Average*, ✗ = *Needs Work.*

➢ **HYBRID VERY GOOD**

✓ ***Practical & Adaptable***

<u>Notes:</u> **(1)** *Scoring relative to each other.* **(2)** *Ease of operating & maintaining power plant.* **(3)** *Output & efficiency improvements.* **(4)** *Average of Categories.*

CONCEPT

TECHNICAL: *End-notes*

A. <u>Gas Turbines</u> *The efficiency of these machines involves compromises between competing considerations, e.g.: optimum speeds of compressors and turbines are inherently not the same; cooling is better served by lower temperatures but better efficiencies require higher temperatures. The hybrid approach allows for much better optimization than ordinarily possible because the firing and cooling air functions are completely separated. Additional improvements include:*

i. The multiple shaft arrangement allows for higher compressor and turbine efficiencies.

ii. A dedicated, inter-cooled compressor delivers lower cooling temperatures which increases efficiency while also reducing power requirements for compressor operation (machine's net output is higher).

i. Cooling air temperatures are further reduced by evaporating water into the compressed air.

The hybrid's integrated thermal cycle is unique, groundbreaking, and represents a new direction for 21st century turbo-machinery and power generation.

B. <u>Support System</u>. *The general philosophy is to allow the outer and inner systems to move largely independently of one another in the horizontal direction while being unrestrained in the vertical direction. Rotating machinery is fixed to the outer turbo-machinery vessel. Turbo-machinery casings are minimally loaded to avoid rotors/stators interference. Interior pressure boundary surfaces are cooled (via helium compressor) to reduce expansion and increase allowable stresses. Cooled bellows & toroidal expansion joints are employed to further accommodate thermal movement.*

D. <u>Nuclear Fuel</u> *Gas reactor fuel has been under development for over 50 years. Current designs employ TRISO (TRIstructural-ISOtropic) fuel particle coatings with the structural objective of insuring that thermally induced stresses & strains do not fracture or crack the particle coatings and thereby release radioactive material. The Hybrid fuel shares this philosophy. However, a pellet coating coupled with more effective cooling, and lower temperatures are also employed to further insure the integrity of both the fuel kernels and pellets. This added protection is aimed at avoiding undue contamination of rotating machinery, although protection of the public is also enhanced.*

The Hybrid manufacturing process is based on an industrial scale effort adhering to strict control to insure compliance with rigorous design and production specifications. The envisioned methods are based on the exceptionally successful German and Japanese programs - **Refs. 20 & 53.** *The Hybrid fuel power densities and thermal gradients are less than those of the German design. Hence, there is no compelling financial reason to employ US methods that are designed for much harsher reactor conditions. The US methods have also had a poor track record in terms of leakage.*

D-1 <u>Fuel Sleeve Assembly</u> *Braided carbon fiber reinforced polymer (e.g. SiC), carbon graphite end fittings employing mechanical connections.* ***Proprietary Design.***

CONCEPT

D-2 Fuel. *Key elements include:*

(i) <u>Particle</u>. External Sol-Gel precipitation process. Uranium dissolved in acid, mixed with alcohol and other additives to form broth. Vibrating nozzle used to form droplets that fall through ammonia gas and drop into concentrated aqueous solution of ammonia for bulk gelation. Gel droplets washed, dried and calcined to remove impurities. Sintering reduces UO_3 to UO_2 particle (~600 μm diameter, density ~104 g/cm^3).

Particle Material	Low-enriched UO_2
Gel-Precipitation	External
Broth	Aqueous
Droplets	Vibrating Nozzle.
Gelation	Ammonia gas & ammonia solution.
Washing	Ammonia
Drying	~80°C
Calcination	Air at ~300°C
Sintering	H_2 at ~1600 to 1700°C

(ii) <u>Kernel</u>. Chemical Vapor Deposition (CVD) process. Pyro-carbon and silicone carbide layers deposited in high temperature fluidized coater. Continuous batch process involves sequential coating of fuel particles without loading/unloading. Kernel diameter ~920 μm.

Kernel Coating Process	Continuous
Buffer (thickness ~60 μm)	<u>Gas</u>: Ar-C_2H_2; <u>Temperature</u>: ~1250°C; <u>Coating Rate</u>: ~ 6-10 μm/min.
Middle Pyrolytic Coating (~25 μm)	<u>Gas</u>: Ar-CH_2-C_3H_6; <u>Coating:</u> ~1300°C; <u>Coating Rate</u>: ~ 4-6 μm/min.
SiC Coating (~25 μm)	<u>Gas</u>: H_2-CH_3-$SiCl_3$; <u>Coating:</u> ~1500°C; <u>Coating Rate</u>: ~0.2 μm/min.
Outer Pyrolytic Coating (~45 μm)	<u>Gas</u>: Ar-C_2H_2-C_3H_6; <u>Coating:</u> ~1300°C; <u>Coating Rate</u>: ~ 4-6 μm/min.

(iii) <u>Pellet</u>. Kernels over-coated, mixed in matrix (graphite filler and binders), pressed and heat treated into final form. Particle packing ~30%. The Hybrid pellet concept envisions using overcoat carbon and Zirconium Carbide (~45 μm) to protect pellet from mechanical damage that may expose fuel particles leading to coating failures and fission product release. Unlike SiC, ZrC not brittle and should accommodate pellet thermal effects – **Ref. 53**. *Pellet~32mm diameter x ~32 mm high, matrix density ~1.7 g/cm³)*

Element Type	Annular, Multiple Hole Pellet
Matrix Materials/State	Graphite/Powder
Binders	Phenol
Kernel Over-coating	~200 μm in several stages.
Pre-pressing/Pressing	Pellet formed into required shape.
Carbonization	800-900°C in Inert Gas
Heat Treatment	~1950°C in vacuum.
Pellet Overcoats	Chemical vapor deposition.

CONCEPT

E. __Air Turbine & Compressor__. The use of a stand-alone very large air compressor driven by large combustion turbine is essentially the same approach used by GE to factory test each of their combustion turbines prior to shipment of the machines to their customers. In lieu of driving a generator, the combustion turbine rotates an air compressor, which avoids the problems of interfacing the test facility with the electrical grid – see **Ref. 23**.

The helium turbines and compressors are very roughly 5 feet in diameter. Blades are roughly 5 inches high.

F. __Helium Outer Vessel__. Barrel type outer vessel with flanged elliptical heads. ASME Section III vessel constructed of SA 508/533 Carbon steel alloy. Concept based on barrel type compressors used in gas process industry. Vessel diameter approximately 12 feet.

G. __Machine Overhaul__. The helium compressor and turbines hydraulically jacked in and out through ends of outer vessel. The machines are bolted to outlet plenum of the helium compressor. Plenum attached to cooled hot-leg inner pipe. Annular inlet attached to cooled tube linking reactor outlet to turbine inlet. This arrangement is somewhat similar to the use of transition pieces used by combustion turbines – transition pieces deliver hot gas from combustor to inlet of turbine. The plenum is designed to accommodate loads associated with thermal movement of the inner hot-leg piping, thereby avoiding undue loading of helium turbo-machinery casings.

H. __Spent Fuel Storage__. Off-loaded fuel blocks temporarily stored in passively-cooled containment racks, awaiting next refueling. Blocks then moved to spent fuel area where sleeves removed and loaded into inner vessel associated with transport casks. Sealed inner vessels passively cooled awaiting loading into transport casks. Casks staged at on-site underground facility (passively cooled) awaiting shipment to off-site interim facility or permanent underground internment.

I. __Spent Fuel Reduction__. The approximate comparative spent fuel production is calculated based on burn-up tonne of Uranium (U235 & U238) required to produce a megawatt-day of electrical energy. Burn-up for typical conventional water reactor is about 50,000 megawatt (thermal)-days/Tonne-U, which for a typical efficiency of 32% yields 16,000 megawatt (electric)-days/Tonne-U. Gas reactors like the Hybrid have a burn-up of about 110,000 mW(t)- day, **Ref. 1**. *The Hybrid produces 950 Mw(e)/650 mW(t), which means 1 tonne-U yields 165,870 mW(e) -days/Tonne-U. On a normalized basis, the Hybrid produces about 16,500/165,870 or 1/10th the spent fuel generated by a conventional water reactor.*

J. __Core Configuration__. The Hybrid's core configuration is exceptionally flexible for a variety of reasons. The reactor supports rapid block removal and shuffling. The grid (and economics) would normally allow the plant to be shutdown for a few weeks in the spring and fall, which means blocks can be periodically optimally arranged to achieve very uniform fuel burn-up.

K. Advanced Cycle. *Modern heavy-frame combustion turbines are becoming ever more efficient with record-breaking combined-cycle efficiencies (+62%, LHV basis,* **Ref. 26***) achieved largely by increasing firing temperatures, with recent machine temperatures well over 2600°F/1426°C. However, these higher temperatures also lead to higher turbine exhaust temperatures, which leads to ever greater challenges for boilers and steam turbines that use this heat to generate power. Fundamentally, the higher temperatures require steam turbines to operate at higher pressures (+2500 psig/170 bar) and higher temperatures, with both issues creating significant challenges in satisfactorily dealing with allowable material stress levels. These impacts also extend to boilers, with higher fabrication costs and operational problems invariably occurring.*

A potential solution to higher firing temperatures lies with the supercritical CO2 cycle. The genesis of the approach is to replace the Rankine steam cycle with a supercritical CO2 cycle. Supercritical CO2 is a fluid state of carbon dioxide where the fluid is held above the pressure/temperature critical point. The density at that point is similar to that of a liquid.

The promise of the supercritical cycle lies with greater efficiency and much smaller compressors and turbines. However, formidable issues lie with effectively fully utilizing the heat energy as well as deploying practical machinery. Development activities have been underway for several decades, however success remains elusive.

A typical supercritical cycle that relies on partial recompression of CO_2 *to enhance efficiency. A portion of the low-pressure* CO_2 *is re-compressed and joined with flow from the main compressor. However, the characteristics of the re-compressed fluid complicate compressor design. Additionally, the recuperators face "pinch-point" issues where heat transfer becomes poor leading to complicated, expensive heat exchangers..*

Rather than replace the steam cycle, a more practical approach lies with combining Brayton and Rankine cycles to capitalize on their individual strengths. This patent pending new cycle is expected to more readily accommodate the higher firing temperatures of advanced combustion turbines while also more readily accommodating the major swings that occur in today's electrical grid. The steam turbine is more of a standard design that is not required to operate at very high pressures and temperatures. The advantages of the fully integrated cycle lie largely with more reasonable capital costs for the steam turbine and boiler as well as greater operational flexibility. Relative to the baseline hybrid-nuclear cycle, the fully integrated cycle achieves more efficient utilization of the combustion turbine's exhaust energy. This is the result of CO_2/H_2O *use being less constrained relative to only heating and boiling water The fully integrated Hybrid-nuclear cycle is expected to be the 21st century replacement for all conventional nuclear and fossil power plants.*

CONCEPT

L. <u>Helium Turbines</u>. *From an overall perspective, high-temperature gas turbines represent a major improvement over steam technologies owing to their small size and much more favorable economics. In the mid-nineties attempts were made to capitalize on these advantages in conjunction with helium gas reactors that would employ the direct Brayton cycle –* **Ref. 45**. *The technologies available at the time were unable to successfully overcome the problems caused by using helium . However, today's technological advancements have overcome these issues, as summarized below.*

1. *<u>Bearings</u>. Gas turbines typically employ hydrodynamic oil bearings to support the rotating shaft. These types of bearings inevitably leak oil at the shaft/housing interface. However, oil contamination of the reactor is operationally unacceptable due to the severe material issues that will follow from oil contamination of the core.*
   <u>Solution:</u> Magnetic Bearings. *This method (see* **Technical: Helium-Turbine/Magnetic Bearing**) *is now routinely used and has matured to the point where the technology can be used with the Hybrid's small and light-weight multi-shaft turbine/compressor. Cooling of these bearings is required but the nature of the Hybrid' s turbine configuration allows for subsequently using the helium for shaft cooling in a manner similar to that used with modern gas turbines.*
2. *<u>Shaft Leakage.</u> Some efficiency reducing fluid leakage from a shaft/housing interface always occurs. In the case of a reactor, the loss of expensive helium is unhelpful while radioactive contamination can be an issue*
   <u>Solution</u>: Dry gas Seals. *Modern gas turbines have developed a variety of sealing methods that have successfully significantly reduced efficiency robbing fluid leakage – see* **Technical/*He Turbine Compressor* – Shaft Sealing**
3. *<u>Efficiency.</u> The small size of the Helium atom complicates designing and manufacturing efficient blades and stators. The nature of the helium also requires a large number of blades and stators. The technologies of the 1960's were unable to adequately and cost-effectively overcome these problem.*
   <u>Solution</u>: Advanced Design & Manufacturing. *Modern techniques such as computational fluid dynamics have been instrumental in the impressive efficiency gains of today's gas turbines. Further, advanced computer controlled production methods allow the manufacture of the complex blade/stator shapes required to support these high efficiencies. The advent of 3-dimensional printing (already in use with some gas turbines) promises even greater cost improvements.*
4. *<u>Materials</u>. The blade and stator materials of the 1960's were challenged by relatively modest firing temperatures which largely explains the poor efficiencies (~25%) of gas turbines in the era.*
   <u>Solution</u>: Advanced Materials. *Todays gas turbines employ firing temperatures well beyond the needs of the helium turbine. Stators/blades can employ advanced materials but special coatings and exotic materials are not needed*

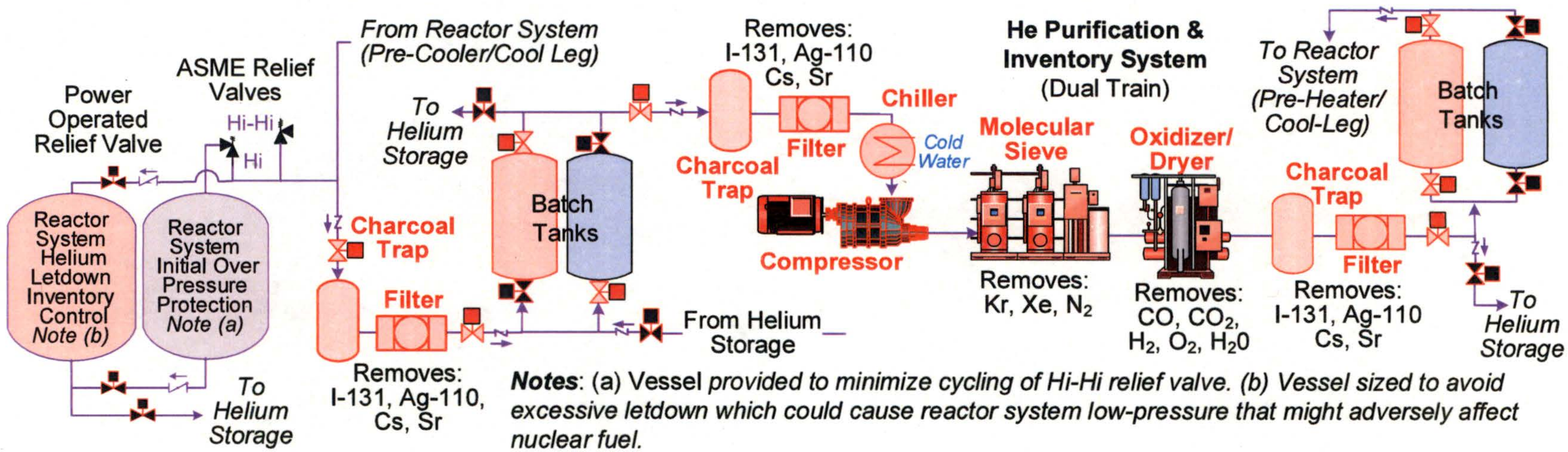
Collectively, these modern improvements allow deployment of practical helium turbines/compressors. In passing, General Atomics was recently awarded a contract for helium turbine development – **Ref 46.**

***M. <u>Helium Filtration.</u>** The filtration of air entering a gas turbine is essential for proper performance of today's advanced machines that employ very close tolerances. Key considerations include: erosion which typically occurs from particulates larger than 5 to 10 microns (average particle size in atmosphere ~7 microns); and fouling which involves sticky materials adhering to surfaces –* **Ref. 41.** *Helium machines face these same issues but radioactive contamination is also a concern owing to complications that can arise during machine maintenance and overhaul. However, these issues are unlikely due to the following:*

i. Erosion. As a closed system, particulates are almost entirely associated with fine graphite dust generally caused by movement of the core's graphite blocks. – **Ref 42**. *In order to avoid erosion, in-line, removable sintered metal filters (nominally 5 micron filtration) are used on the inlet side of the pre-heater – see* **TECHNICAL**: ***Heat Exchangers***.

ii. Fouling. The helium gas is exceptionally pure. Contamination, e.g. from moisture ingress, is highly unlikely as nuclear steam generators are not used.

iii. Radioactive Contamination. The Hybrid's fuel operating and accident temperatures are well below the point at failures of the fuel particles are likely. The fuel pellets are also coated. A slip-stream clean-up system is also employed, see below.



Notes: (a) Vessel *provided to minimize cycling of Hi-Hi relief valve. (b) Vessel sized to avoid excessive letdown which could cause reactor system low-pressure that might adversely affect nuclear fuel.*

Chiller unit designed to be readily replaced; condensable fission product gases will plate out on unit. Collectively, these features will insure that the helium compressors & turbines will operate properly with minimal to no contamination issues.

See **Appendix D,** Table D3, items D, E, F, & G for further discussion.

CONCEPT

__Historical Perspective__

The production of power has always involved friction between economics and adverse public health impacts typically associated with pollution discharges from the generating facilities. Generally pollution reductions and attendant health improvements occur through profit motivated technology innovations stimulated by government legislation associated with the broad recognition of the damaging effects on the public caused by releasing harmful material into the environment.

Typically, catastrophic failures at conventional power plants do not physically adversely affect the public, provided the public is located away from the immediate vicinity of the facility.

Unlike conventional power plants, the routine operation of nuclear power plants does not pose any noteworthy public health risk. However, catastrophic failure can radioactively contaminate vast stretches of territory and potentially threaten the public with lethal levels of radiation. The financial implications of such catastrophes are also staggering.

Owing to the potential radiation threat to the public, nuclear reactors rely on a number of methods to avoid catastrophic failure. However, because of the very concentrated nature of the nuclear heat source, electrical power and water are essential to avoid disaster. As demonstrated by several relatively recent nuclear accidents (e.g. Fukushima), conventional reactors are not risk-free, although the threat probability is small.

SAFETY

- PROTECTED

CONCEPT

SAFETY: *Summary*

- **PASSIVELY FAIL-SAFE**
  - ✓ *No Power*
  - ✓ *No Water*
  - ✓ *No Operators*[1]
  - ✓ *Fuel Cannot Melt*

- **PUBLIC & INVESTMENT ALWAYS PROTECTED**
  - ✓ *Multiple Barriers - Full Containment*
  - ✓ *Diverse Passive & Diverse Active Cooing*

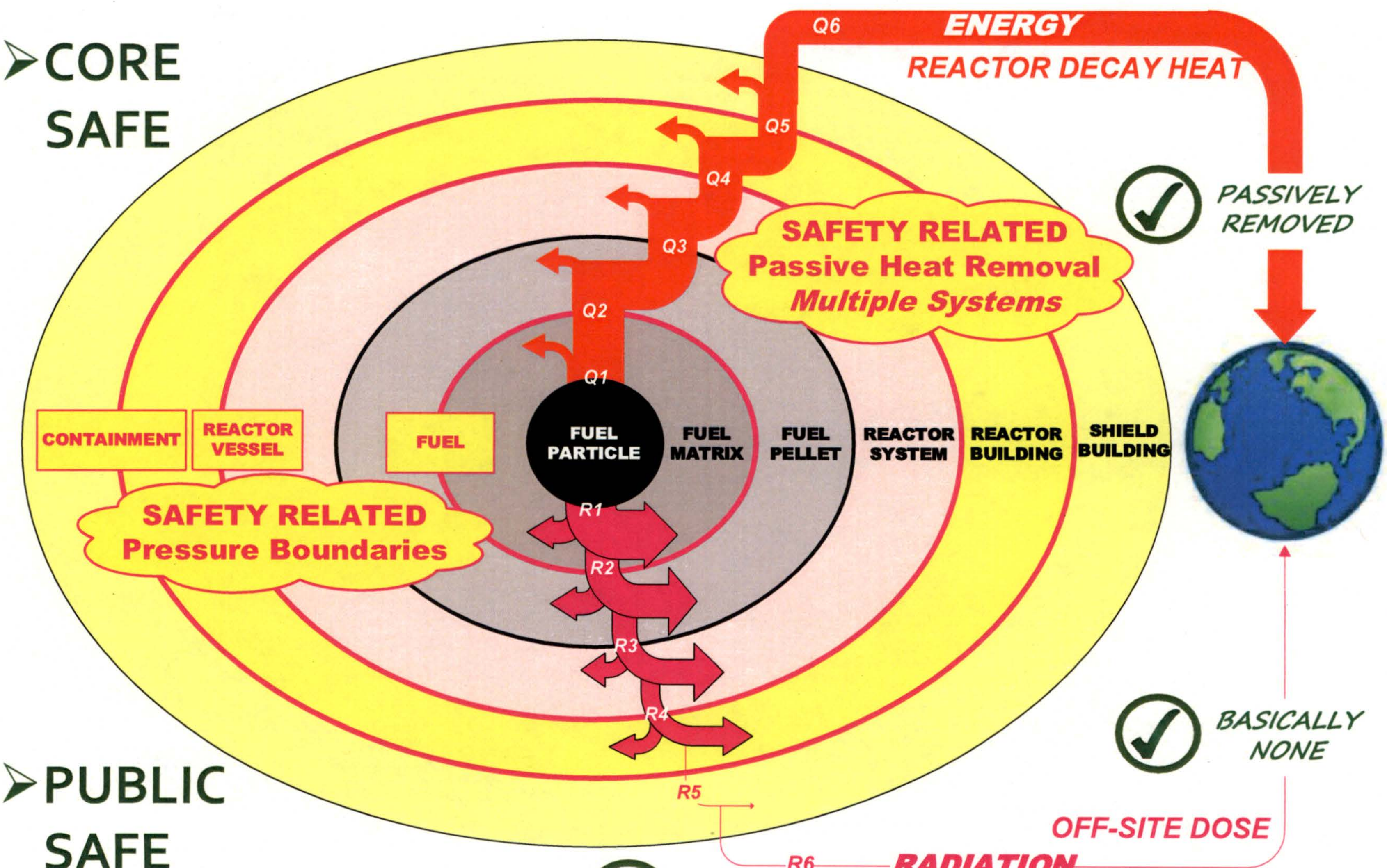
✓ INSPIRES PUBLIC CONFIDENCE

Note: **(1)** The primary function of the plant operators is to protect the asset. Protection of the public is ultimately provided by fully passive measures that do not require operator intervention.

CONCEPT

SAFETY: *Reason Why*

➢CORE SAFE



➢PUBLIC SAFE

✓ Emergency Planning Zone < ¼ mile

CONCEPT

SAFETY: *Key Capabilities*

- **PUBLIC NOT AFFECTED**
  - ✓ *Fires*
  - ✓ *Floods*
  - ✓ *Tornados*
  - ✓ *Explosions*
  - ✓ *Earthquakes*
  - ✓ *Aircraft Impact*
  - ✓ *Reactor Problems*
  - ✓ *Electrical Blackouts*

✓ *INSPIRES PUBLIC CONFIDENCE*

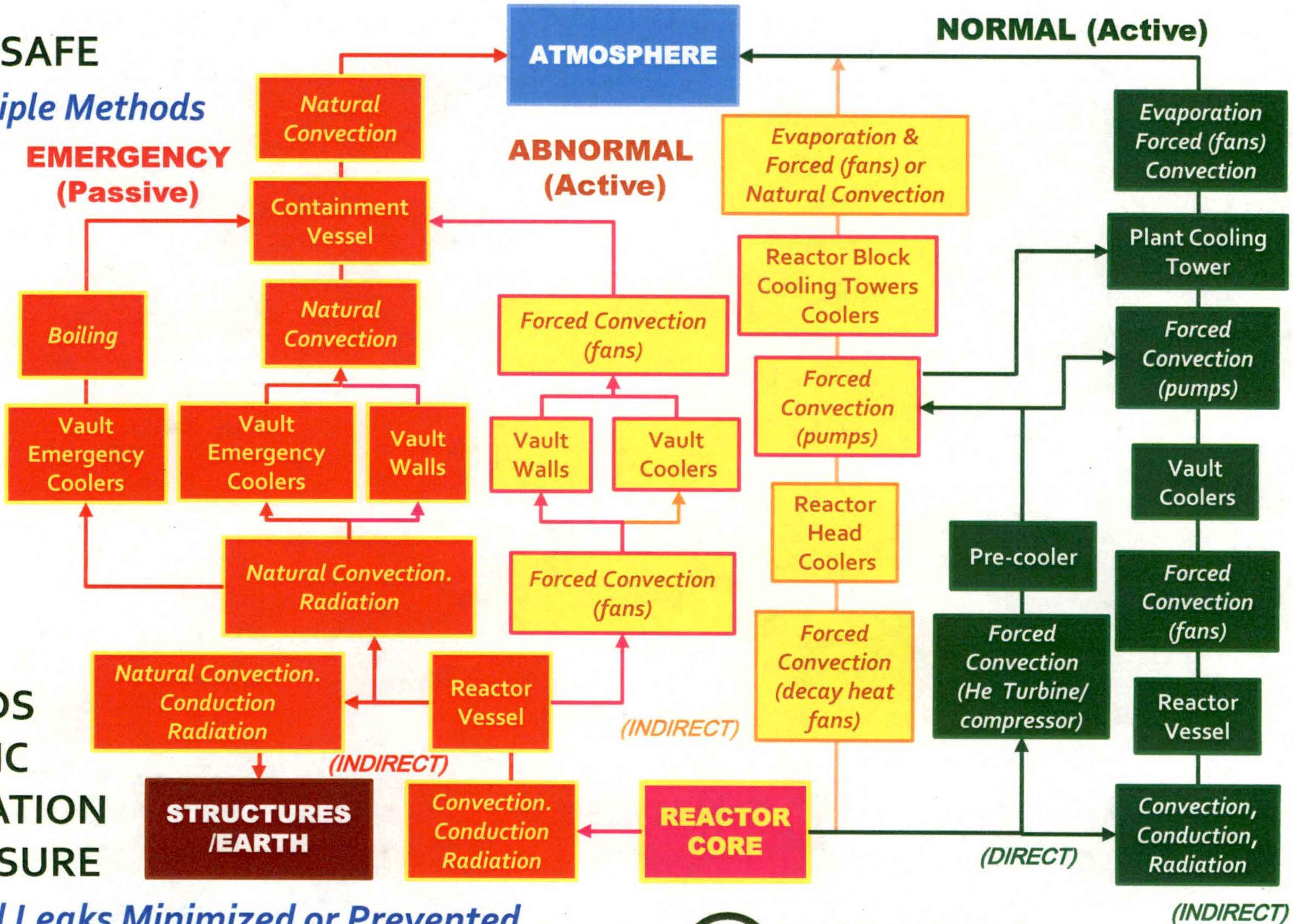
Major Event/ Emergency	Results[1]	Protection[2]
Loss of Load (Generator)[3]	Core Temperatures Well Below Limits	Reactor Gradually Reduces Power
Loss of all AC Power	Core Temperatures Well Below Limits	Active Core Cooling (DC Powered)
Loss of All Power	Core Temperatures Below Limits	Passive Core Cooling
Small or Large Hole in Reactor System	Core Temperatures Well Below Limits	Active Core Cooling
	Core Temperatures Below Limits	Passive Core Cooling
Gas Pipeline Explosion	Reactor Not Affected	Reactor Outside Blast Zone

<u>Notes</u>: *(1) Fuel Barrier (coatings) not breached. (2) Containment provides additional back-up protection. (3) Primary compressor operation unaffected by loss of generator. Loss of load typically major challenge (thermal induced stresses causing structural failures) for power plants.*

CONCEPT

SAFETY: *Core Cooling*

- **FAIL-SAFE**
  - ✓ *Multiple Methods*



- **AVOIDS PUBLIC RADIATION EXPOSURE**
  - ✓ *Fuel Leaks Minimized or Prevented*
    - Heat Removed Faster Than Produced

INSPIRES PUBLIC CONFIDENCE

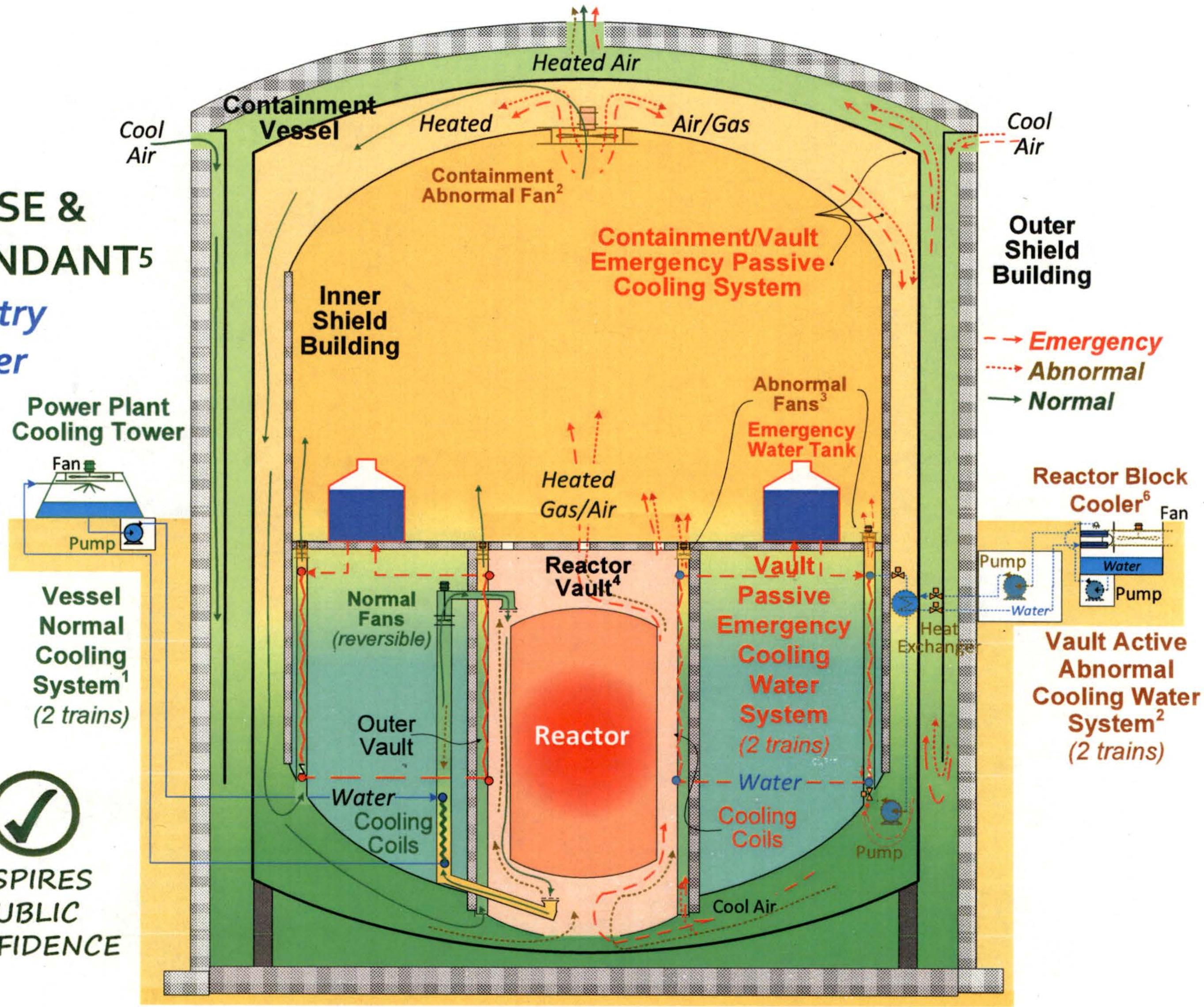
CONCEPT

SAFETY: *Reactor/Vessel Heat Removal*

Hybrid-Nuclear Energy

➢DIVERSE & REDUNDANT5

✓*Industry Leader*



INSPIRES PUBLIC CONFIDENCE

Notes: *(1 cooling w electrical* ***(2)*** *Powe Essential Electrical*

(3) Powered by Essential DC electrical system. (4) Metal liner protects outer vault concrete from excessive heat. (5) Helium turbine/compressor preheater, pre-cooler can also remove reactor heat. (6) Dry/wet cooling unit.

CONCEPT

SAFETY: *Decay Heat System**

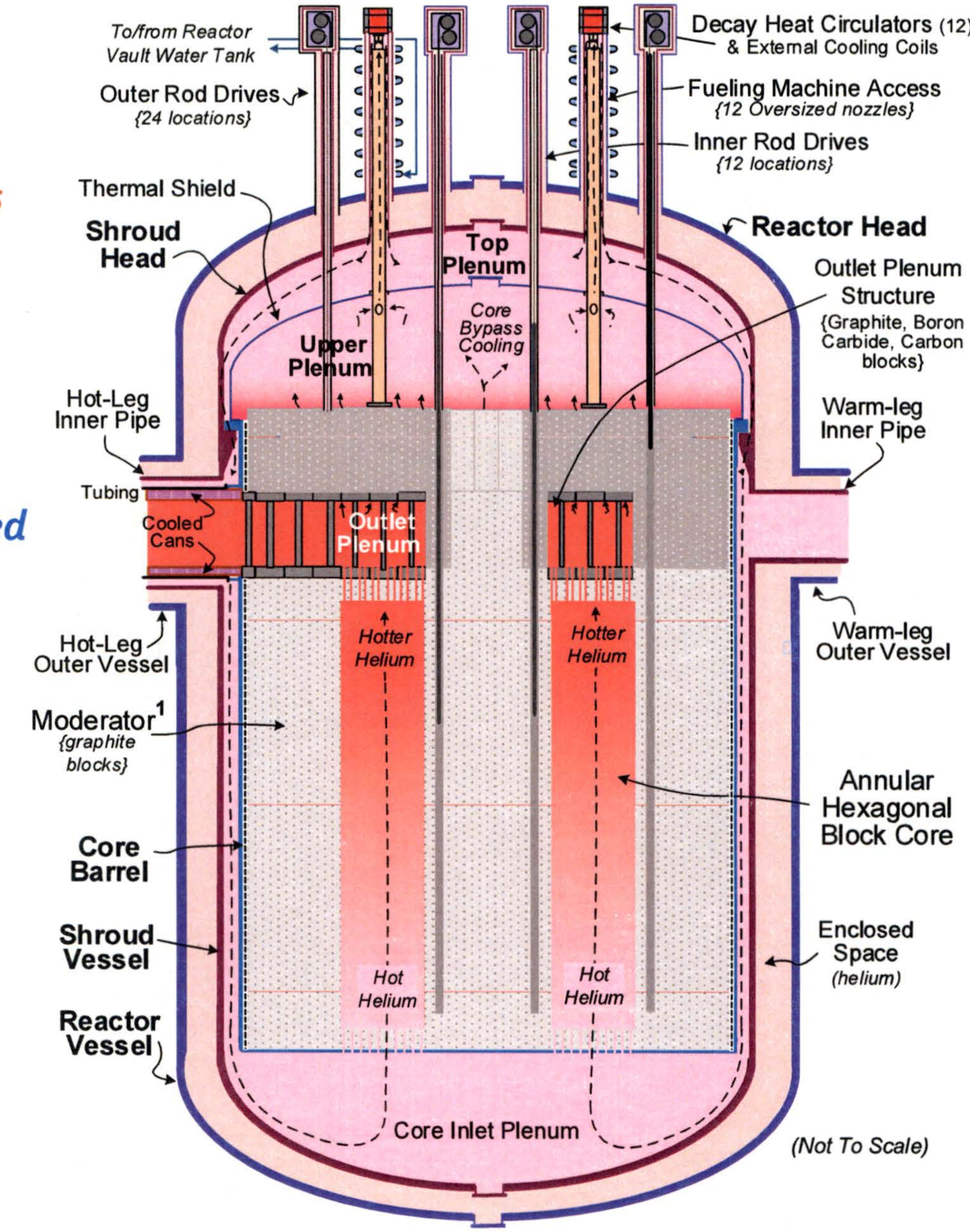
/Active

Hybrid-Nuclear Energy

** Abnormal Situations*

➢ **SIMPLE & RELIABLE**

✓ *Helium Circulated within Reactor*[1]



CONCEPT

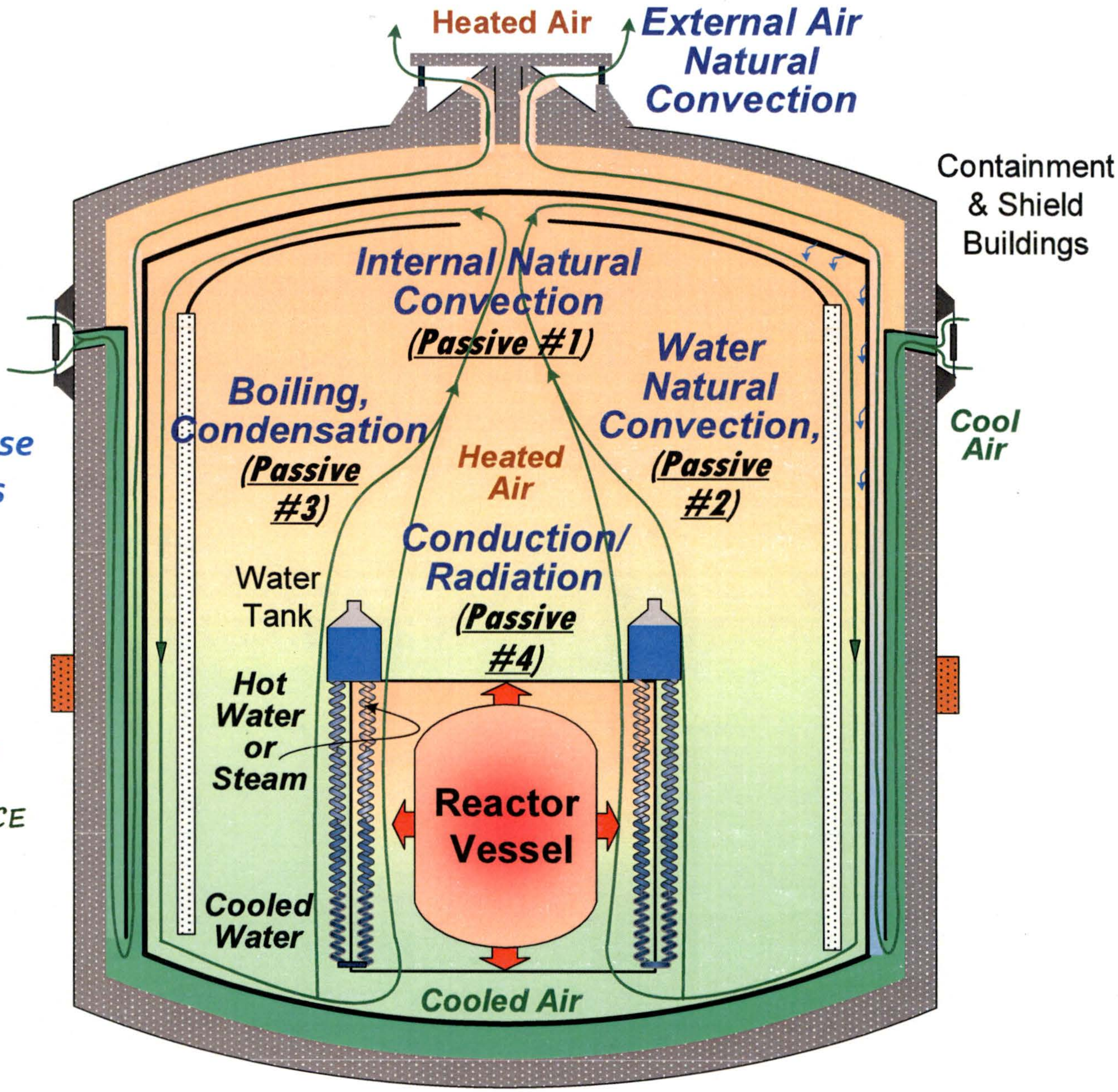
SAFETY: *Decay Heat Removal*

/Passive*

** Emergency Situations*

- DEFENSE IN-DEPTH
  - ✓ *Multiple & Diverse Passive Methods*

INSPIRES PUBLIC CONFIDENCE



CONCEPT

SAFETY: *Passive Barriers*

INSPIRES PUBLIC CONFIDENCE

- **DIVERSE & REDUNDANT**
  - ✓ *Leads Industry*
- **PREVENTS UNDUE PUBLIC RADIATION EXPOSURE**

Although highly unlikely that fission products would reach this point, condensable fission products would plate out on internal surfaces.

Outer Shield Building

↑

Containment Pressure Boundary *Safety-Related*

The 3rd **Safety-Related** primary boundary is the impervious steel shell of the containment. Condensable fission gases plate out on internal metal surfaces.

↑

Reactor Building Internal Surfaces

The 5th secondary barrier to fission product release are the internal surfaces of the reactor building on which condensable gases plate out.

↑

Reactor Pressure Boundary *Safety-Related*

The 2nd **Safety-Related** primary boundary is the impervious steel reactor pressure boundary. Condensable fission gases plate out on internal metal surfaces.

↑

Reactor System Internal Surfaces

The 4th secondary barrier are the reactor system's internal metal surfaces on which condensable gases plate out. Graphite dust & fission products (if present) – are normally removed by the purification system and pre-heater's in-line sintered metal filters.

↑

Core Structures

The 3rd secondary barrier is the core's graphite whose high amorphous carbon content absorbs metallic fission products, e.g. strontium, europium & actinides.

↑

Fuel Pellet

The 2nd secondary barrier to fission product release is the fuel pellet's carbon matrix & outer coatings, both of which hinder fission product release

↑

Fuel Kernel Outer Coating *Safety-Related*

The 1st **Safety-Related** primary barrier to core radionuclide release is the fuel kernel's essentially impervious silicone-carbide outer coating.

↑

Fuel Kernel Inner Coatings & Fuel Particle

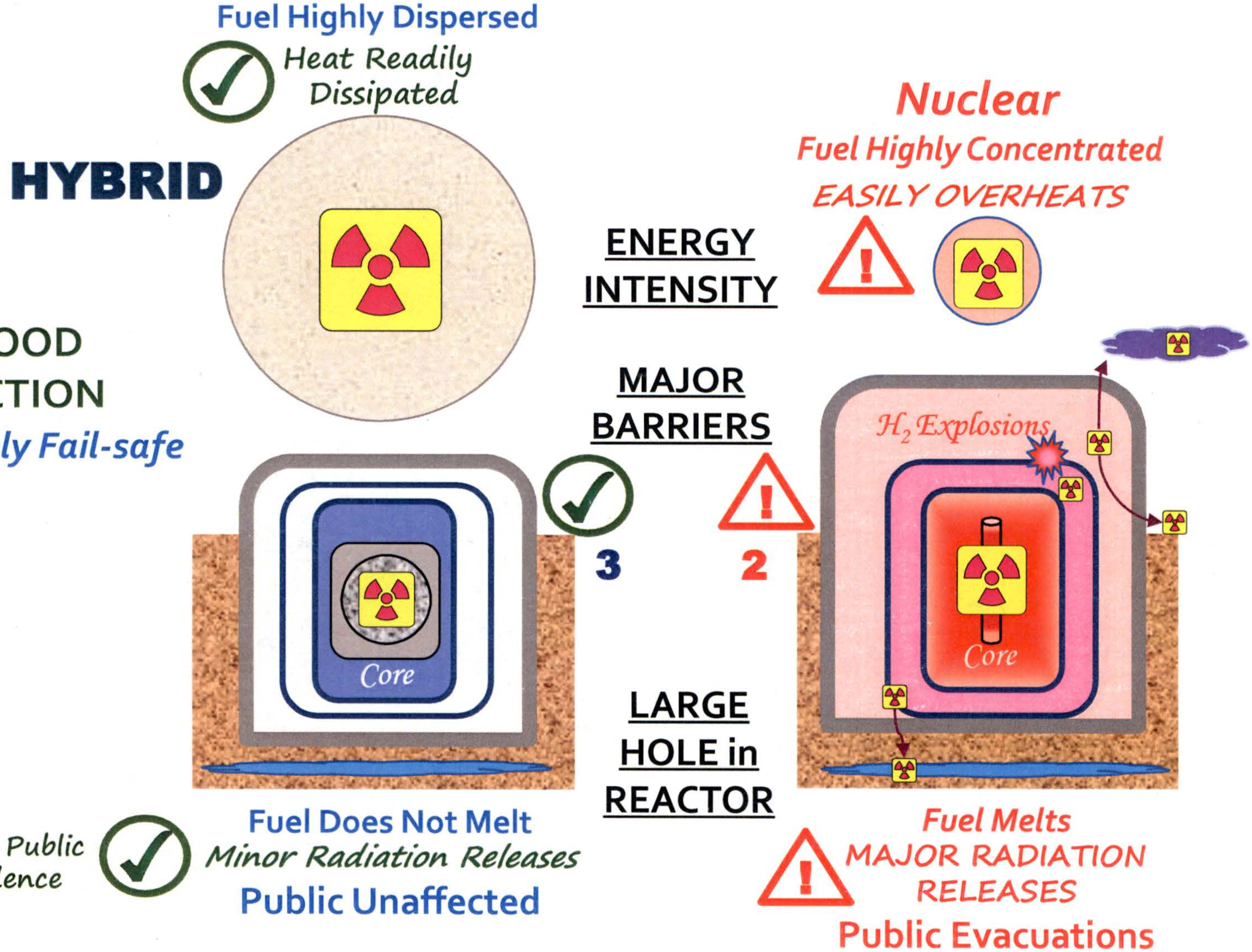
The 1st secondary barrier to core radionuclide release is the fuel particle which normally contains 95% of short-lived fission gases such as Kr-88 & I-131.

The fuel kernel's inner coatings hinder fission product release.

CONCEPT

SAFETY: *Contrast*
/Overview

➢VERY GOOD PROTECTION
✓*Passively Fail-safe*



Inspires Public Confidence

CONCEPT

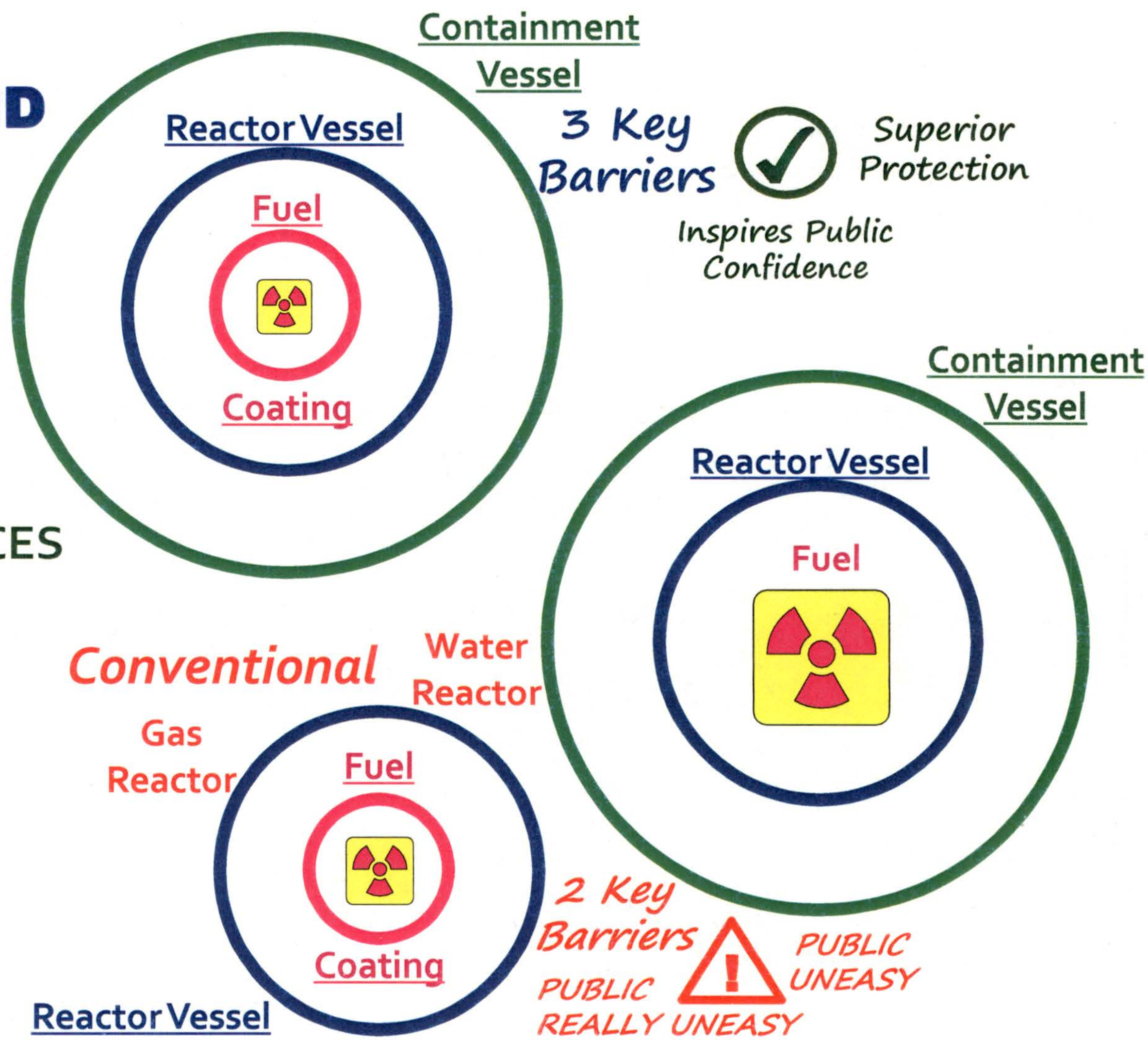
SAFETY: *Contrast*

/Passive Barriers

HYBRID

➢ MULTIPLE PRIMARY DEFENCES
- ✓ *Fuel Particle Coatings*
- ✓ *Reactor Vessel*
- ✓ *Full Containment*

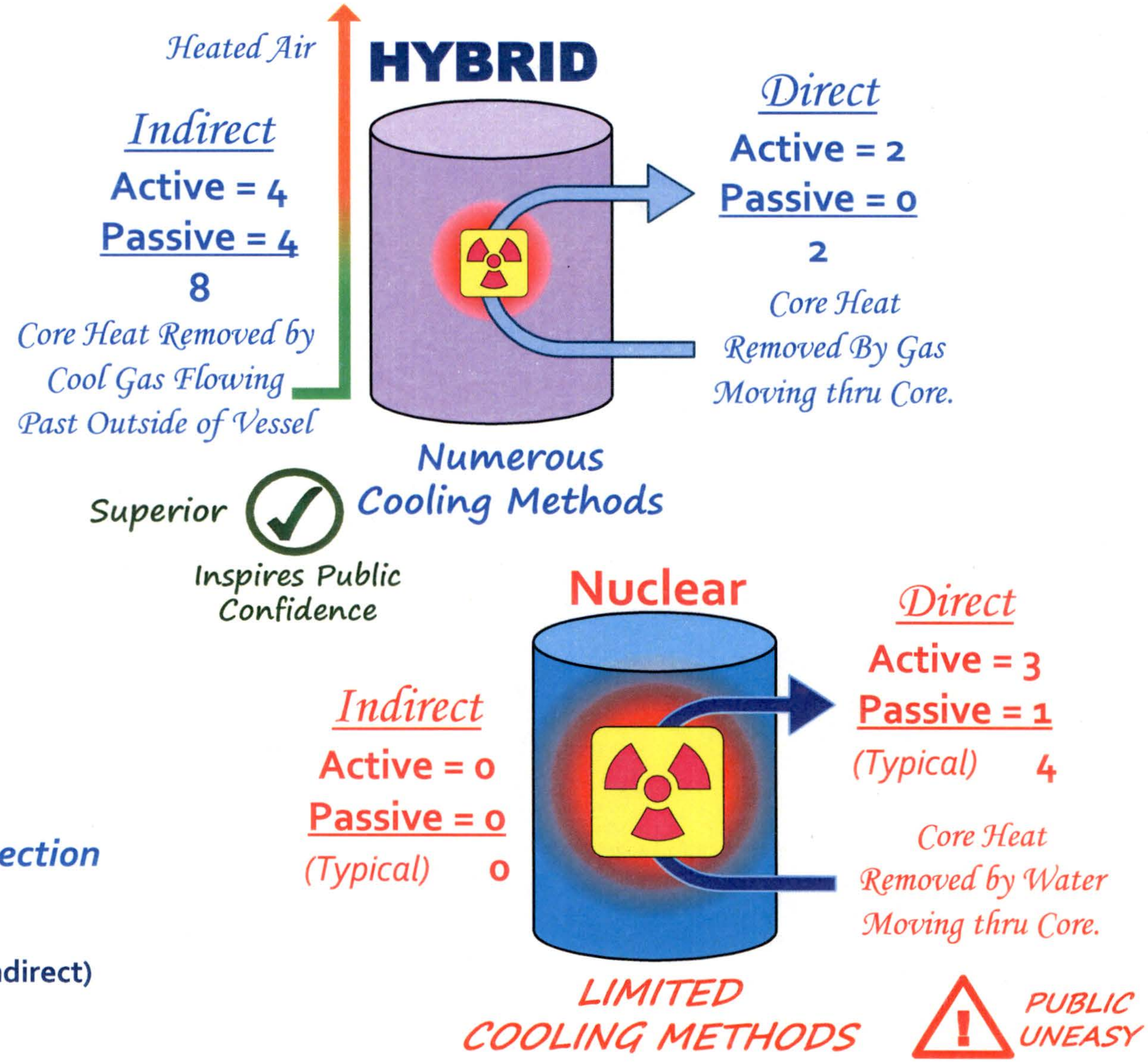
➢ MULTIPLE SECONDARY DEFENCES
- ✓ *Radioactive Materials Absorbed & Plated out*



CONCEPT

SAFETY: *Contrast*
/Core Cooling

- **OVERHEATING PREVENTED**
  - ✓ *Avoids Fuel Leaks*
- **NORMAL**
  - ✓ *Forced Circulation*
    - (Direct)
- **ABNORMAL**
  - ✓ *Forced Convection*
    - *Circulation* (Direct)
    - *Ventilation* (Indirect)
- **EMERGENCY**
  - ✓ *Passive Natural Convection*
    - *Ventilation* (Indirect)
    - *Boiling* (Indirect)
    - *Conduction/Radiation* (Indirect)



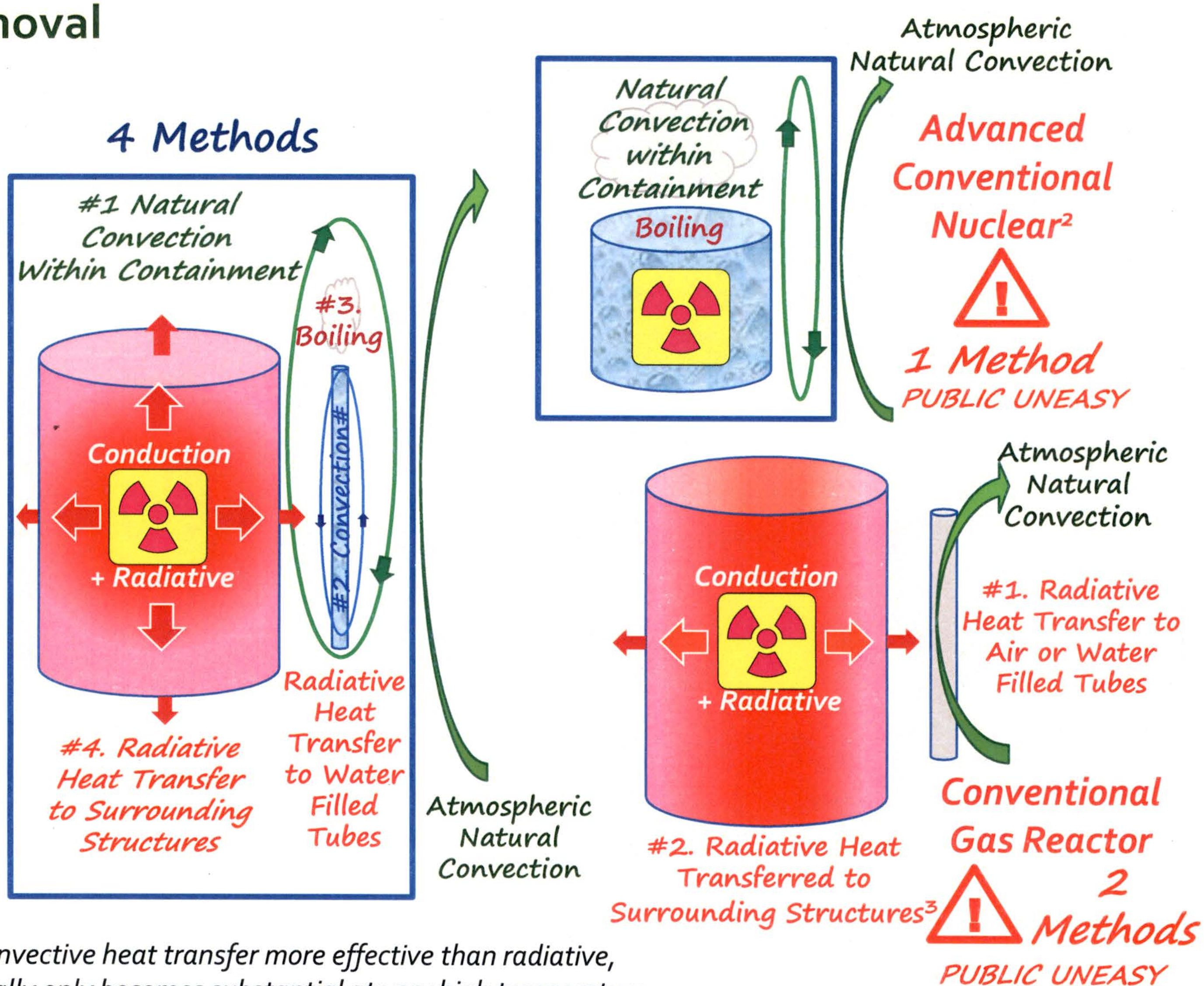
CONCEPT

SAFETY: *Contrast*
/Passive Heat Removal

HYBRID

➢BEST[1]
- ✓ *Exceptionally Reliable*
- ✓ *Highly Effective*

Inspires Public Confidence

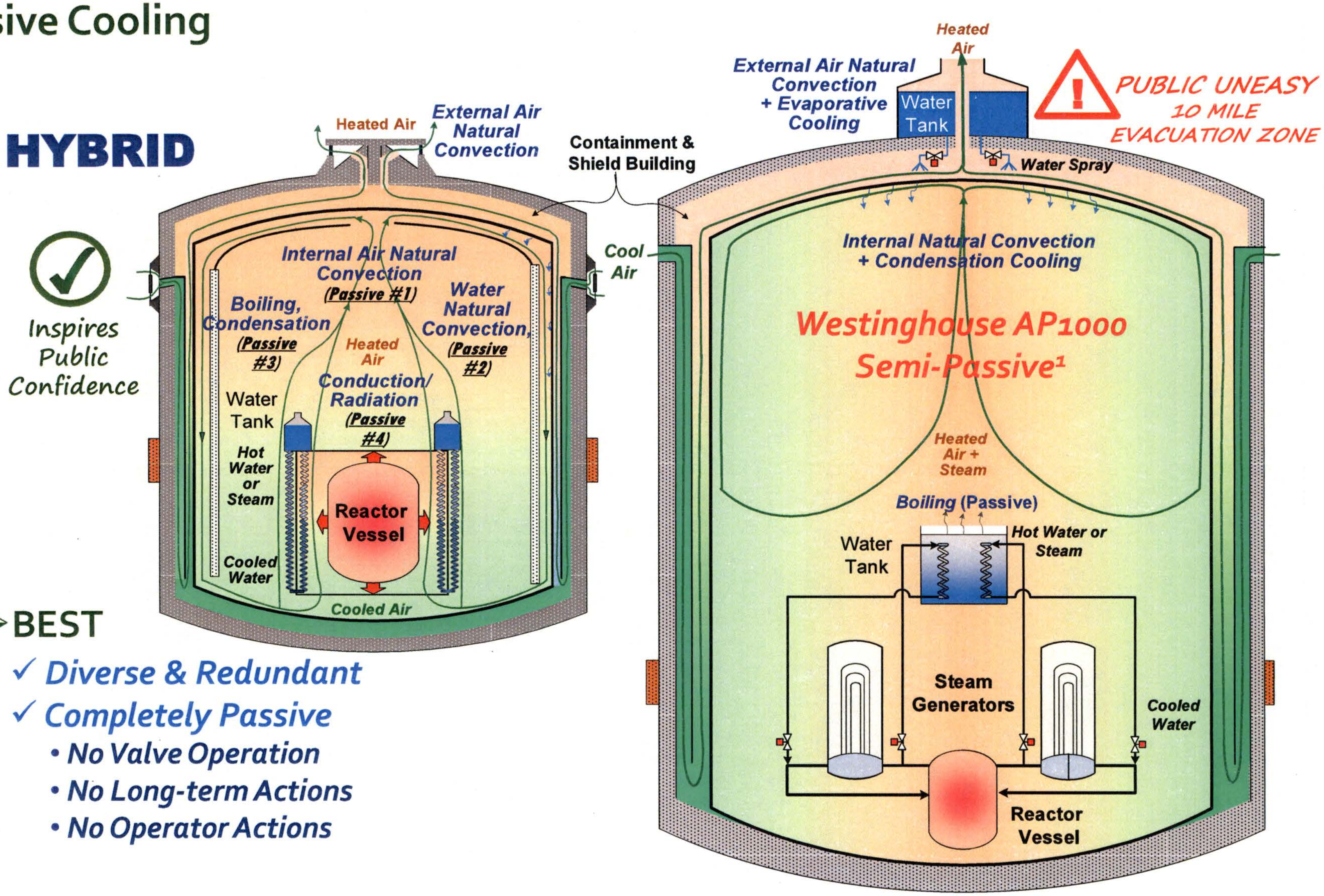


Note: *(1) Convective heat transfer more effective than radiative, which generally only becomes substantial at very high temperature differentials (typically +1000°F/537°C)* – **Ref. 47.** *(2) AP1000 water reactor* – **Ref. 2.** *(3) Top & bottom of vessel insulated* – **Ref. 42**

CONCEPT

SAFETY: *Contrast*

/Passive Cooling



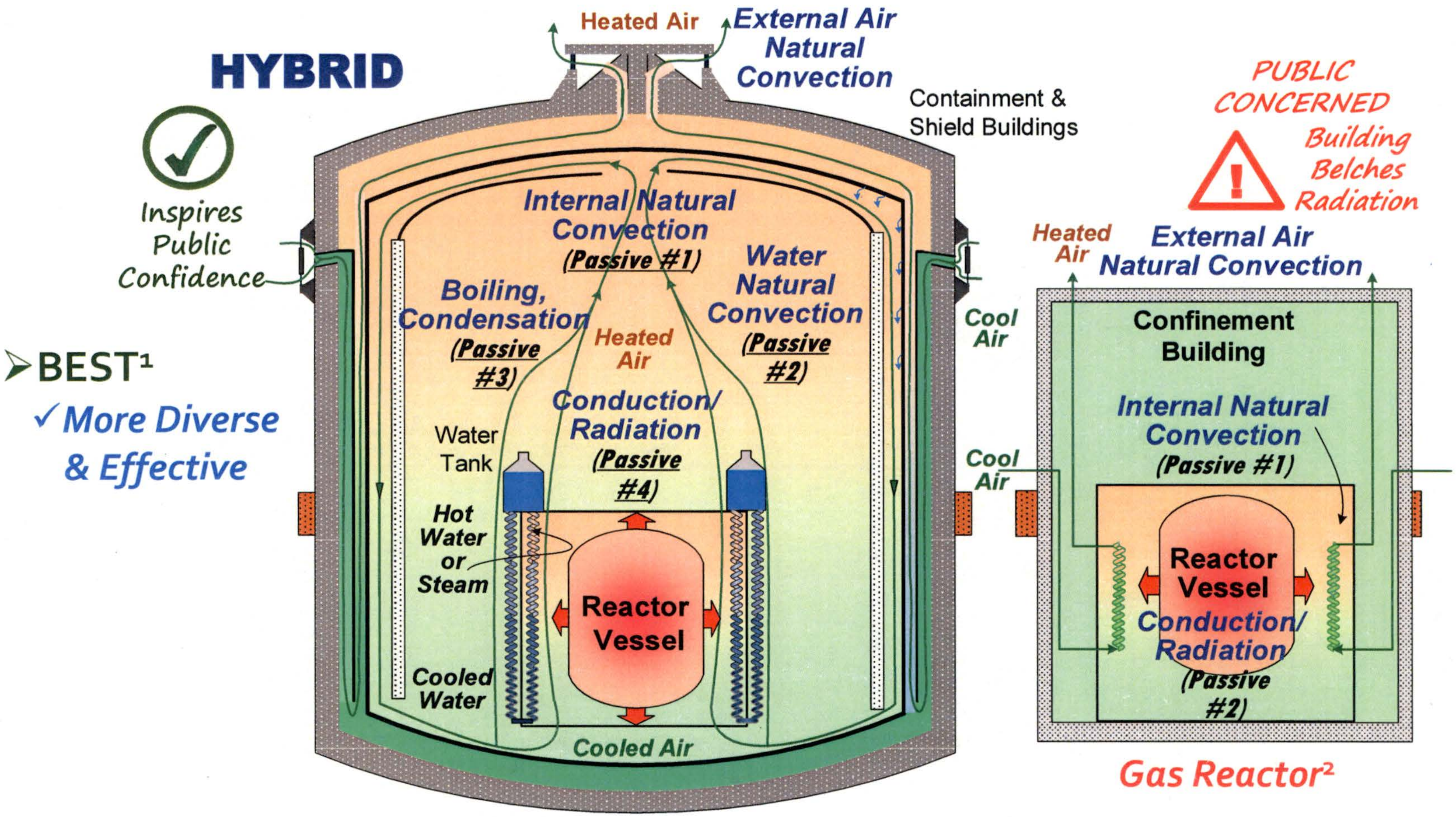
➤ **BEST**

- ✓ *Diverse & Redundant*
- ✓ *Completely Passive*
  - *No Valve Operation*
  - *No Long-term Actions*
  - *No Operator Actions*

CONCEPT

Note: *(1) Active valve operation required + operator action @ ~ 3 days to avoid fuel melting/damage* – **Ref.2**

SAFETY: *Contrast*
/Passive Cooling

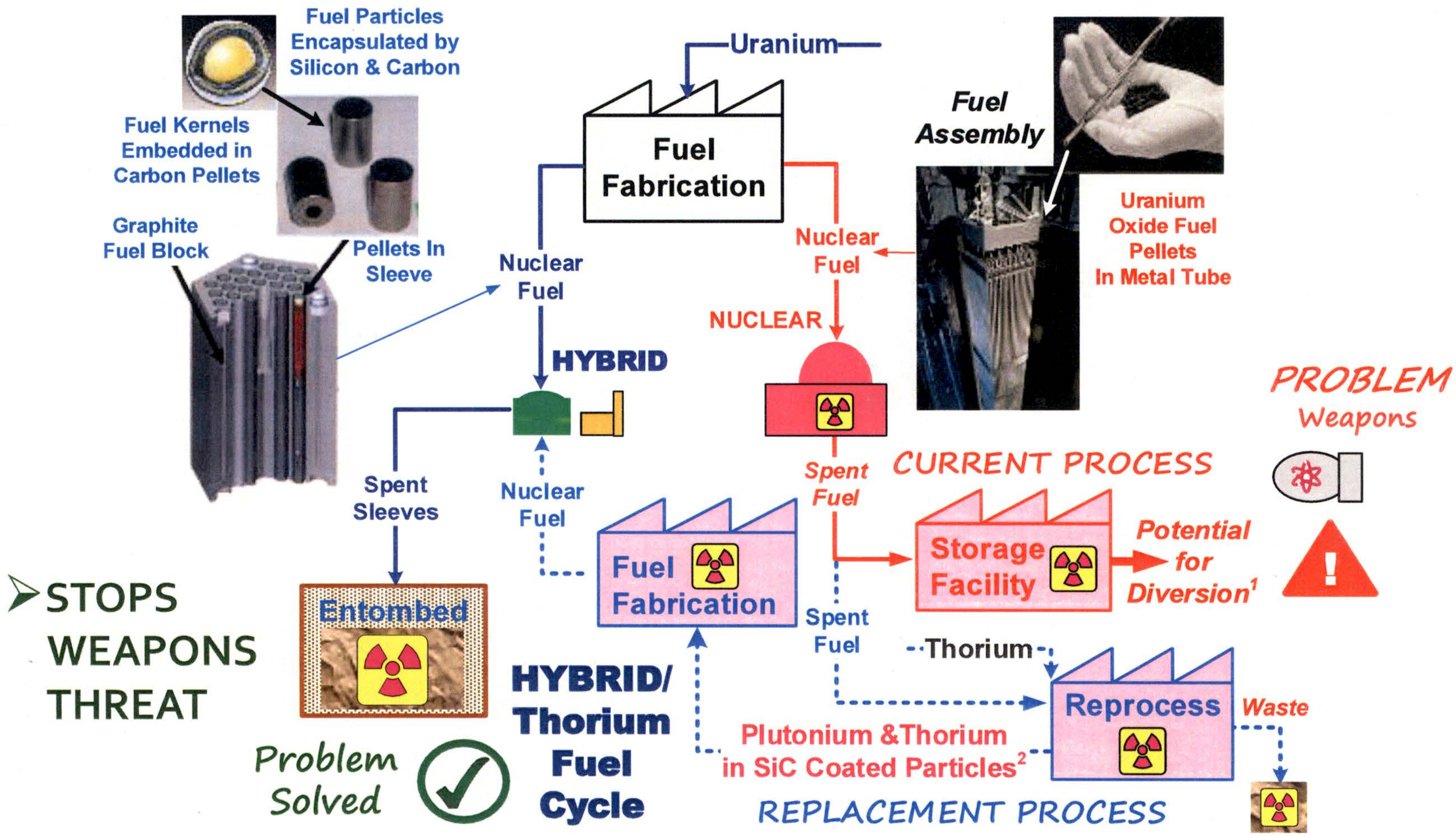


Note: **(1)** *Passive #1 relies on convective heat transfer from outside vessel wall to air circulating by natural convection within containment. Passive #2 system relies on radiation and convection between reactor vessel and cooling coils, with water circulation and boiling by natural convection.* **(2)** *Relies primarily (~75%,* **Ref.43***) on radiation heat transfer to cooling tubes that circulate outside air by natural circulation from atmosphere. Also, lacks containment which can lead to substantial leakage and potentially undue public radiation exposure.*

CONCEPT

SAFETY: *Contrast*

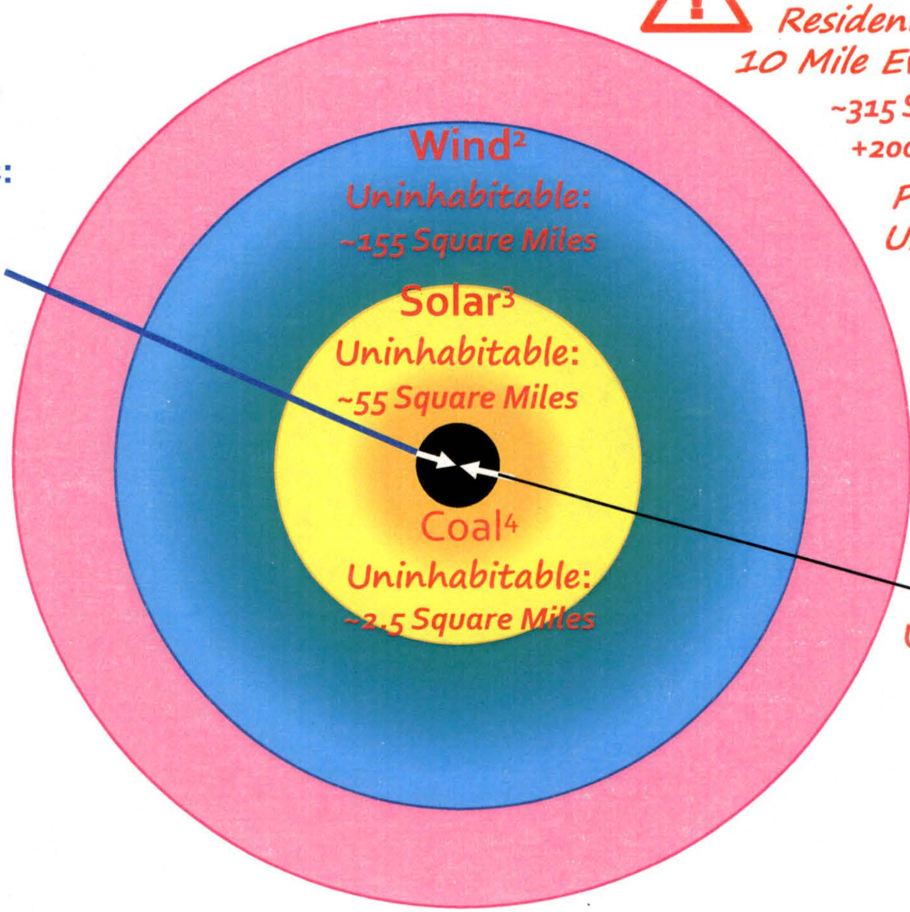
/Proliferation



Note: **(1)** *Spent fuel can be intentionally diverted or stolen, with material subsequently fashioned into a crude "dirty" bomb whose detonation would create terror and massive clean-up costs (tens of $ millions). The actual nuclear explosive damage would be relatively small because the Pu isotopes in spent fuel cause an inefficient, poor chain reaction.* **(2)** *Silicone Carbide fuel particle coating essentially impervious to reprocessing.*

CONCEPT

SAFETY: *Contrast*
/Public Direct Impacts[1]



➢ **NO ISSUES**

✓ *Nearby Populations Unaffected*

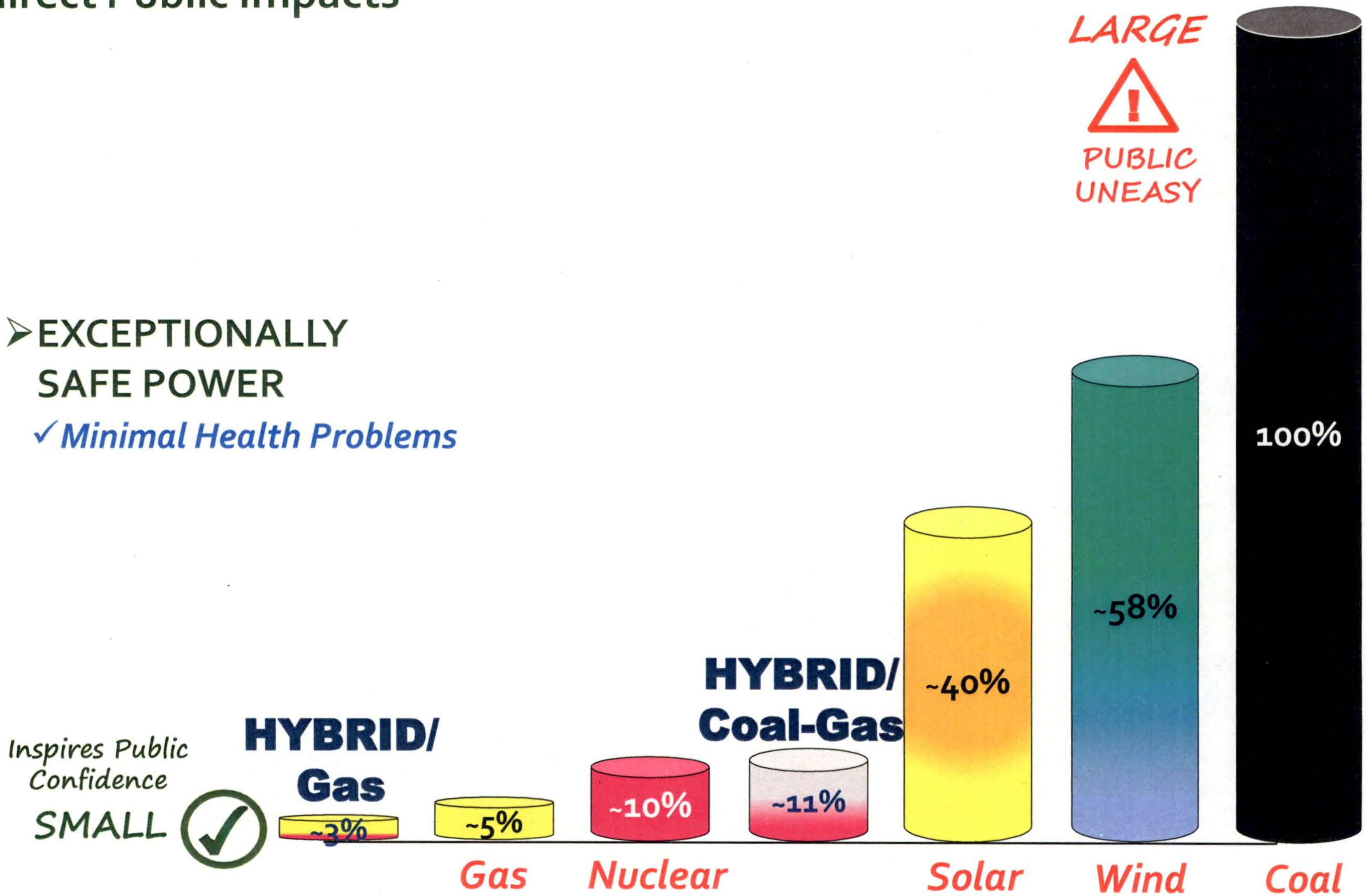
Notes: ***(1)*** *All assumed to produce ~7.8 million MWh in a year.* ***(2)*** *Using* **Ref. 54** *debris/missiles & noise ~7.5 x machine height or ~655 ft. for 2.5 MW machine x 1270 machines –* **Ref. 57**. ***(3)*** *Site boundary, 35,000 acre plant.* ***(4)*** *Site boundary, 1600 acres.* ***(5)*** *Site boundary, 15 acres plus 50 feet, National Fire Protection Association Code.* ***(6)*** *10CFR50.47. Regulations also require a ~50 mile (~ 7850 square miles) food contamination zone. Hybrid equivalent is 1.75 mile zone (~2.5 square miles).* ***(7)*** *See* ***LICENSE: CONTRAST*/Public Radiation**

CONCEPT

SAFETY: *Contrast*

/Indirect Public Impacts[1]

- **EXCEPTIONALLY SAFE POWER**
  - ✓ *Minimal Health Problems*



Note: *(1) Average relative risk associated with the total energy cycle,* **Ref. 14**. *HYBRID/All-Nuclear risk factor ~4%.*

CONCEPT

SAFETY: *Contrast*

/Risk – *Advanced Reactors*[1]

★ = *Best*
✓ = *Average*
✗ = *Needs Work*

Reactor Type	Core Damage[2]	Containment Safety	Proliferation Threat	Overall Risk[3]
Conventional	~10^(-05)	Moderate	Medium	✗
Liquid Metal[4]	<10^(-05) ?	Medium ?	Moderate	? ✗+
Fast Reactors[4]	<10^(-05) ?	Medium ?	Moderate	? ✗+
Liquid Fueled[4]	<10^(-05) ?	Medium ?	Moderate	? ✗+
Modular Nuclear (SMR)[6]	>10^(-06)	Good	Medium	✓
Advanced Conventional[5]	~10^(-07)	Very Good	Medium	✓+
HYBRID[7]	**<10^(-08)**	**Best**	**Low**	★

➢ **HYBRID BEST**

✓ ***Vanishingly Small Risk***

<u>Notes</u>: ***(1)*** *Assessment developed from* **Ref. 31. (2)** Estimated probability per year of reactor of major damage, all normalized for 1000 MW(e) output. ***(3)*** *Net scoring relative to each other.* ***(4)*** *As a group, liquid metal, fast reactors and liquid fueled reactors present significant technical challenges. The probability of damage to the reactor is considered a concern while public safety may or may not be an issue. The historical record suggests reactor issues are likely* – **Refs. 24 & 33** . ***(5)*** *Westinghouse AP1000* - **Ref. 59. *(6)*** *Per* **Ref 58,** *NUSCALE 1x10^-07 X 20 reactors ~2x10^-06.* ***(7)*** *Engineering judgement by Hybrid Power Technologies*

CONCEPT

SAFETY: *Rankings*
/Nuclear Plants

CATEGORY[1]	HYBRID	*Gas Reactors*	*Water Reactors*
Passive Containment	☆	✗	✗
Passive Core Cooling[2]	☆	✓	✗
Reactor Risk	☆	✓	✗
Proliferation Risk	☆	☆	✗
Public Protection[3]	☆	✓	✗
NET[4]	☆	✓	✗

☆ = *Best*, ✓ = *Average*, ✗ = *Needs Work.*

- HYBRID SUPERIOR
  - ✓ *Inspires Public Confidence*

<u>Notes</u>: **(1)** *Scoring relative to each other.* **(2)** *Several diverse and redundant methods available and no active measures (e.g. valve operation) required to cool core.* **(3)** *Probability of Design Basis off-site releases.* **(4)** *Average of categories.*

! CONCEPT

SAFETY: *Rankings*
/Power Plants

CATEGORY[1]	HYBRID	*Gas*	*Solar*	*Nuclear*	*Coal*	*Wind*
DIRECT	★	★	✓	✗	✓+	✗
INDIRECT	★	★-	✓	✓+	✗	✓
NET[4]	★	★-	✓	✓-	✓-	✗+

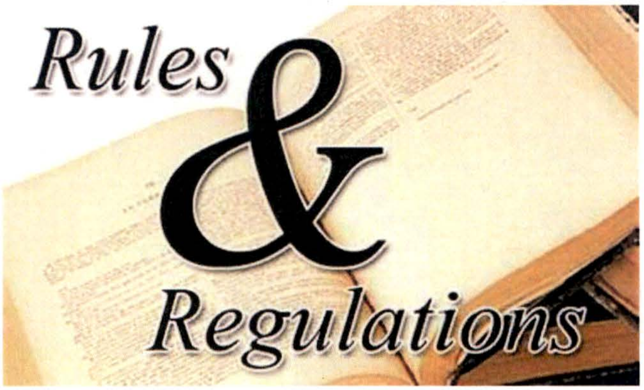
★= *Best*, ✓= *Average*, ✗= *Needs Work.*

➢HYBRID GOOD

✓ ***Protects Public & Investment***

CONCEPT

Notes: *(1) Category scoring relative to each other. (2) Net is average of categories.*



Historical Perspective[1]

While nuclear power's potential for essentially unlimited energy was quickly recognized, the potential for disaster also became apparent as demonstrated by various early experiments and accidents. Regulations were developed, but the primary driver behind early US rules was preventing other countries from developing nuclear weapons.

As the fledgling US nuclear industry grew during the middle of the 20th century, so too did the attendant government agency which oddly was also charged with promoting the industry. This conflict of interest was overcome when the Nuclear Regulatory Commission was created in 1975.

Nuclear regulations evolved over time, with surges in complexity occurring after major accidents (e.g. Three Mile Island, Chernobyl, and Fukushima). These complications can be traced back to greater unease over the ability of conventional reactor cores to avoid melting as a result of inadequate cooling. Such melting can release stunning levels of radiation, hence the need for special measures to protect the public. However, as with most government activities, the subsequent number of regulations tend to take on a life-in-and-onto themselves with ever more extensive rules generated by unaccountable bureaucrats and occasionally by elected politicians.

Note: *(1)* **Ref. 29** *provides a historical summary of the development of US nuclear regulations.*

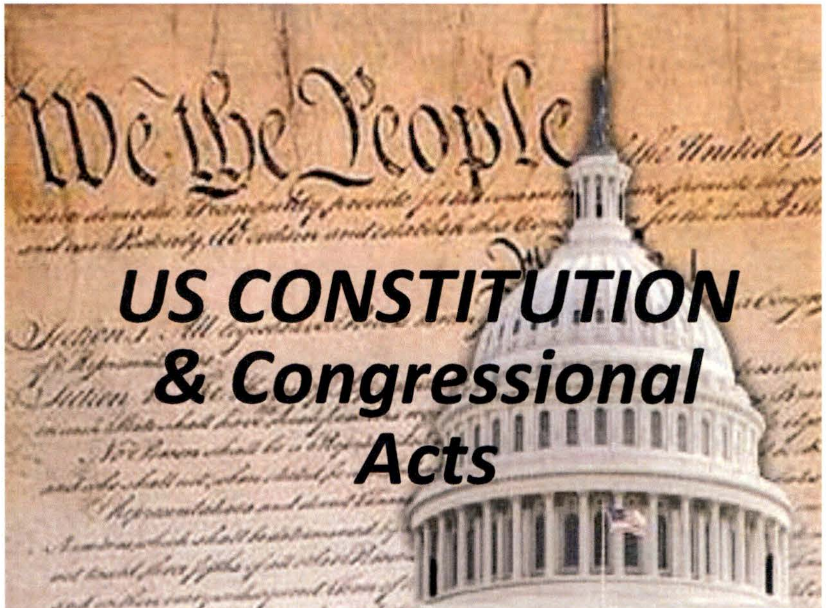
LICENSING: *Summary*

U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

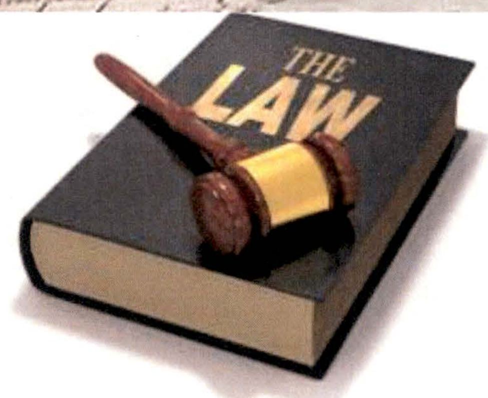
UNITED STATES • ENVIRONMENTAL PROTECTION AGENCY •

CONCEPT

LICENSING: *Laws*

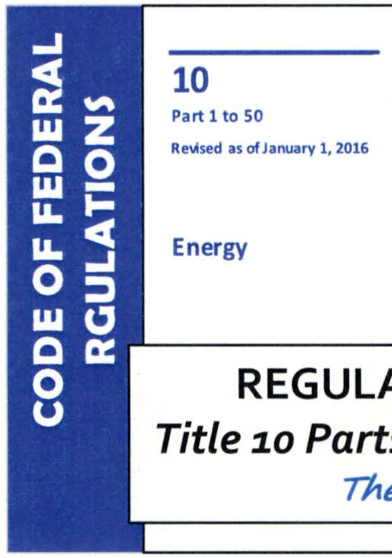


- ➢ COMPLIES
  - ✓ *Laws Enacted by US House & Senate*



CONCEPT

LICENSING: *Regulations*



- **HYBRID MEETS NRC REGULATIONS**
  - ✓ *Changes to Existing Rules Not Necessarily Required.*
    - *Complies with Current* General Design Criteria & Quality Assurance Criteria[1]

... but Current Lower-tier Guidance Needlessly Expensive & Time Consuming for Advanced Reactors[2]

REGULATIONS UNDER LAW
Title 10 Parts 1 thru 199 & Appendices
The NRC Regulations

NRC INTERPRETATION of TITLE 10
Standard Review Plan

NRC Advice
Regulatory Guides

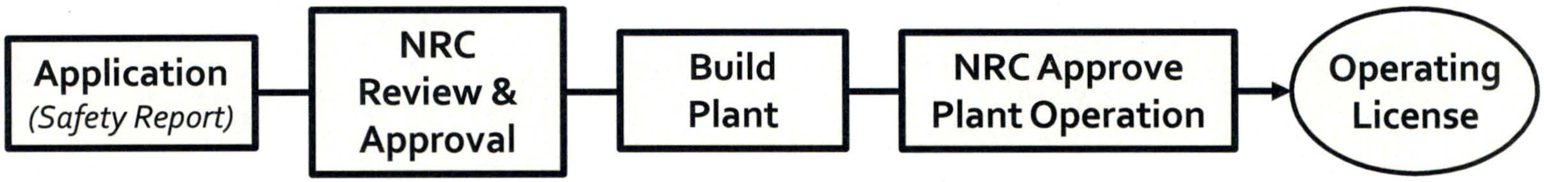
NRC- Nuclear Regulatory Commission

The current regulatory process is directed at water reactors whose fuel can melt. Advanced reactors like the hybrid are demonstratively several orders of magnitude safer due to the use of passive core decay heat removal, passive barriers, and in the case of the, the fuel cannot catastrophically fail. The existing NRC regulations are unquestionably overly restrictive for advanced reactors like the Hybrid, although the Hybrid meets the actual NRC regulations (AKA Code of Federal Regulations).

Note: ***(1)*** *See chapter End-notes, item* ***A****.* ***(2)*** *See Chapter End-notes, items* ***B*** *thru* ***D****.*

LICENSING: *Overview*

- ➢ **GAS REACTORS PREVIOUSLY LICENSED[1]**

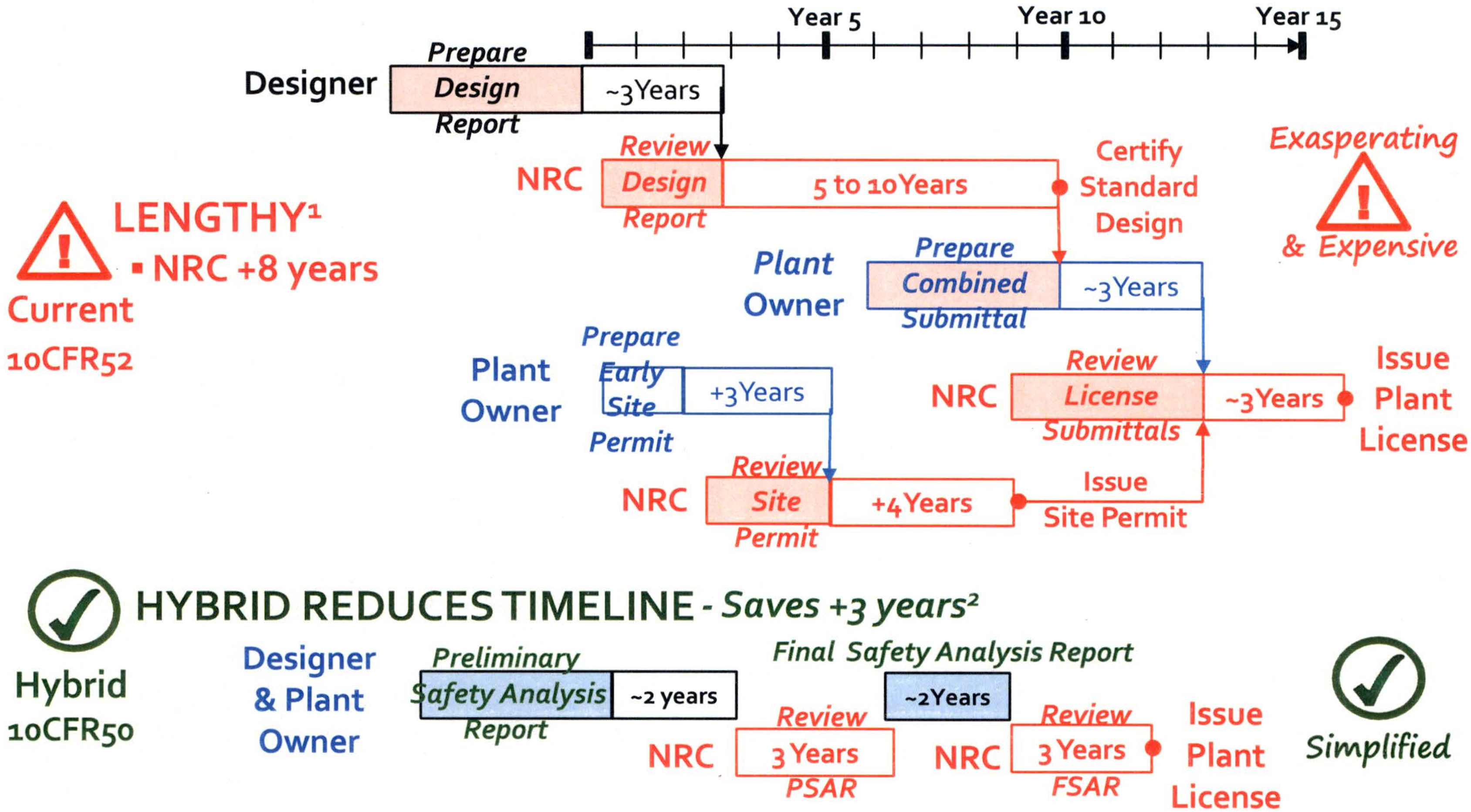


- ➢ **HYBRID EASILY MEETS NRC GOALS for SAFER ADVANCED REACTORS[2]**

<u>Notes:</u> **(1)** *Several gas reactors have been previously licensed in the US, notably the Peach Bottom in early1960's and Fort St Vrain in late 1960's. However, these licenses were issued by the Atomic Energy Commission, not the NRC.* **(2)** NRC *goals* **(Ref. 51)** *include: (a) Highly reliable and less complex shutdown and decay heat removal systems; (b) Simplified safety systems; (c) Designs that minimize the potential for severe accidents; (d) Safety-system independence from power production; (e) Designs that incorporate defense-in-depth; (f) Designs with features to prevent a simultaneous loss of containment integrity (including situations where the containment is by-passed) and the ability to maintain core cooling as a result of an aircraft impact.* See **Appendix E** *for details.*

CONCEPT

LICENSING: *Timeline*

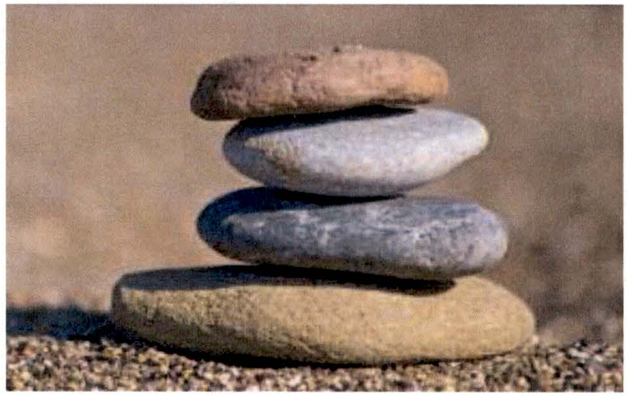


Note: *(1) NRC certification average* - **Ref. 35.** *(2) See* **PROBLEMS** *Chapter End-notes item* ***K***.

LICENSING: *Contrast*
/Regulations & Rules

HYBRID

FEWER PROBLEMS



Nuclear

TOO COMPLICATED

Hundreds "Rules, Guides, Positions"

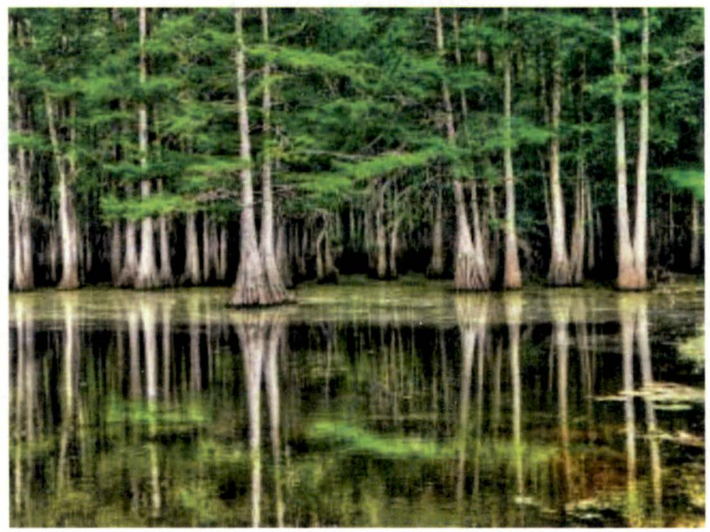
CONCEPT

LICENSING: *Contrast* /Effort

HYBRID

EASIER

- *Core Passively Cooled*
- *Fuel Cannot Melt*
- *Full Containment*
  - *Also Passively Cooled*

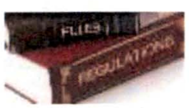


TOO COSTLY[1]

- *NRC Nearly $75 Million*[1]
- *"All-in" $~1/2 Billion*[2]

Fuel Melting Unhelpful

Nuclear



CONCEPT

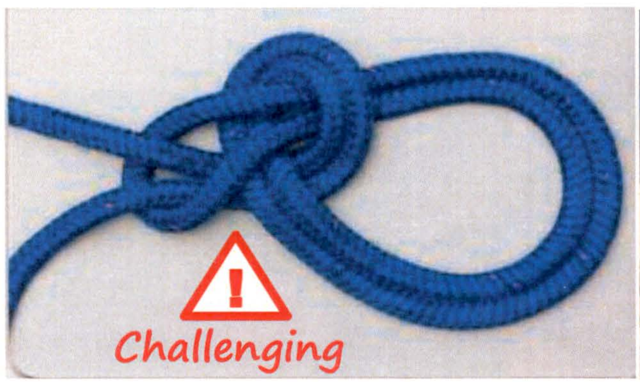
<u>Note</u>: (1) *See chapter End-notes, item* ***E.*** (2) *See* **PROBLEMS** *End-note item* **K**

LICENSING: *Contrast* /Complexity

HYBRID

✓ MORE MANAGEABLE[1]

- *Public Unaffected by Reactor*
- *~50% Fewer Sub-Tier Guidance[2]*
- *~60% Fewer Accidents/Events[3]*
- *+60 % Fewer Regulated Components[4]*



Nuclear

<u>Note:</u> ***(1)*** *Relative to conventional nuclear plant.* ***(2)*** *Simple review of applicable regulatory guides.* ***(3)*** *See "Serious Events" sub-chapter section.* ***(4)*** *Hybrid greatly improves upon NUSCALE advanced passive water reactor that has 2/3 reduction in safety systems relative to conventional reactor* - **Ref.36.** However, on a comparable net generation basis, the large advanced reactors have a lower net core damage frequency – see **SAFETY: *Contrast*/Risk – Advanced Reactors.**

CONCEPT

LICENSING: *Contrast*

/Events

Calming ✓ | ⚠ Unnerving

EVENT	HYBRID[1]	Gas Reactor	Water Reactor
Small Coolant Leak	MINOR {2}	Moderate {2}	Moderate {2}
Large Coolant Leak	MINOR {1}	MAJOR {1}	MAJOR {1}
Control Rod Ejection	NONE {0}	Moderate {1}	Moderate {1}
Failure to Trip Reactor	NONE {0}	Moderate {1}	Moderate {1}
Fuel Melting	NONE {0}	NONE {0}	MAJOR {1}
Fuel Burning	NONE {0}	MAJOR {1}	MAJOR {1}
Water Flooding Reactor	NONE {0}	MAJOR {1}	MAJOR {1}
Hydrogen Gas Explosion	NONE {0}	MAJOR {1}	MAJOR {1}
Steam Generator Tube Rupture	NONE {0}	Moderate {2}	Moderate {2}
Steam Generator Tube Ruptures	NONE {0}	MAJOR {1}	MAJOR {1}
Loss of All AC Power	MINOR {2}	Moderate {2}	Moderate {2}
Loss of All Power	MINOR {1}	Moderate {1}	MAJOR {1}
Aircraft Impact	MINOR {1}	Moderate {1}	MAJOR {1}
NET	NO IMPACT	Evacuations Possible	Evacuations Probable

PUBLIC IMPACTS

MINOR or NONE	No Evacuations
Moderate	Some Evacuations
MAJOR	Large-scale Evacuations

EVENT LIKLIHOOD

{0}	Not Possible
{1}	Unlikely
{2}	Will Occur

➢ FAR FEWER PROBLEMS[2]

✓ *Less Costly*

✓ *Faster Licensing*

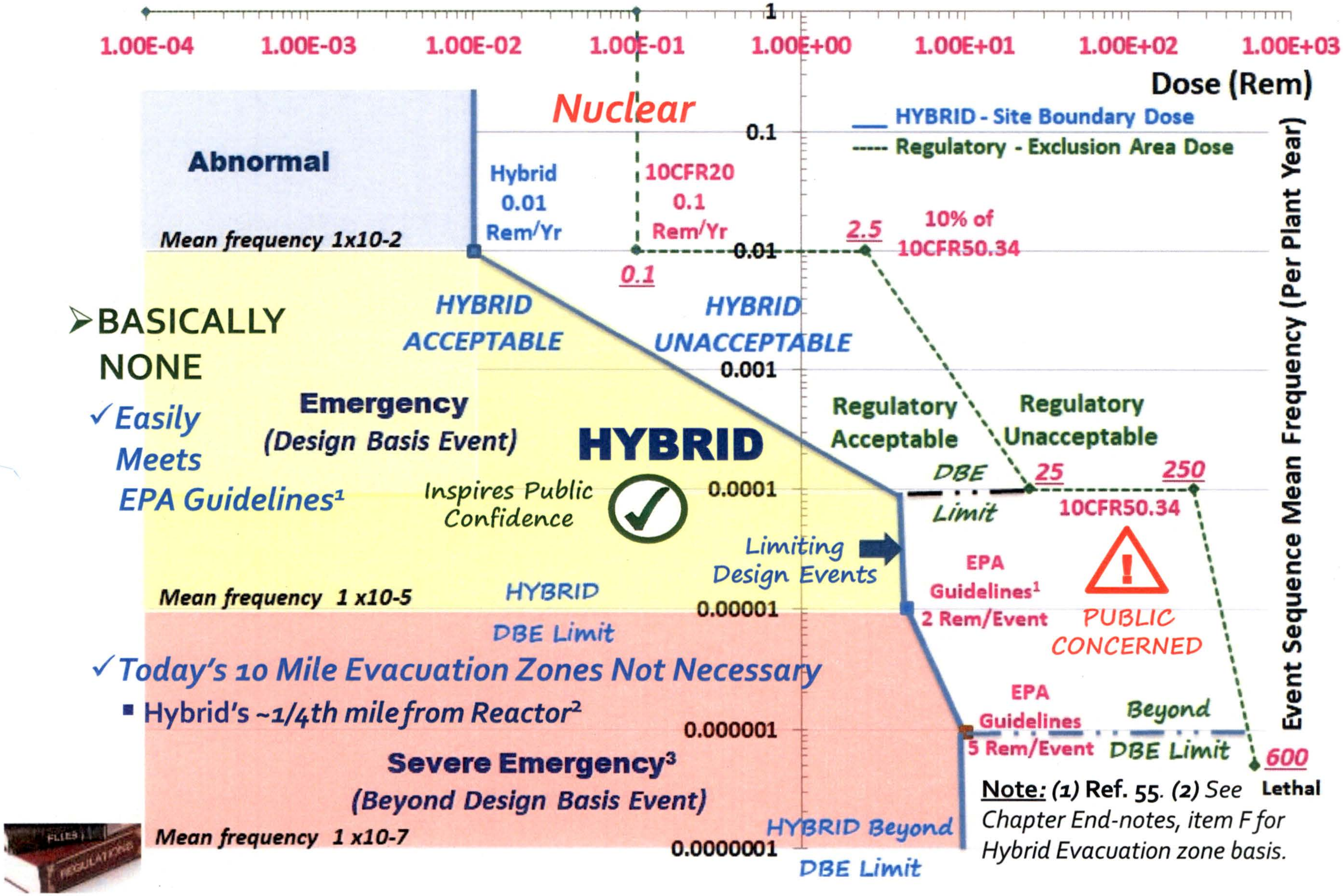
✓ *Inspires Public Confidence*

<u>Note</u>: ***(1)*** *Hybrid Fuel ultimately passively cooled; fuel damage highly unlikely. Containment prevents release of radioactive material The Hybrid employs 3 diverse shutdown methods: trip rods, maneuvering rods, & pellets released by fused links.* ***(2)*** *See* **Appendix D** Tables D2 thru D7 *for more in-depth discussions.*

CONCEPT

LICENSING: *Contrast*

/Public Radiation Exposure



CONCEPT

LICENSING: *Rankings*
/Nuclear Plants

CATEGORY[1]	HYBRID	*Water Reactors*	*Gas Reactors*
Meets Laws & Regulations	★-	★	✗
Minimal Major Accidents	★	✗	✗+
Evacuation Zones	★	✗	✓
Previously Licensed	✗	★	✓-
Reasonable Cost	★	✗	✓+
NET[2]	✓+	✗+	✗+

★ = *Best,* ✓= *Average,* ✗= *Needs Work.*

- ➤HYBRID BEST
  - ✓ *Fewest Complications*

Notes: *(1) Scoring relative to each other. (2) Average of Categories.*

CONCEPT

LICENSING: *Rankings*
/Power Plants

CATEGORY[1]	*Gas*	**HYBRID**	*Nuclear*	*Wind & Solar*[2]	*Coal*
Meets Laws	★	★	★	✗	★
Meets Regulations	★	★	★	✓	✗
Previously Licensed	★	✗	★	★	★
Reasonable Time Frame	✓+	✓	✗	★	✗
Reasonable Cost[3]	★	✓	✗	✗	✗+
NET[4]	★-	✓+	✓	✓	✗+

★ = *Best,* ✓ = *Average,* ✗ = *Needs Work.*

➢**HYBRID SOUND**

✓ *Readily Certified*

Notes: *(1) Scoring relative to each other. (2) Law compliance issues: Migratory Bird Act, Endangered Species Act, etc. (3) Per unit of energy production. (4) Average of Categories.*

CONCEPT

LICENSING: *End-Notes*

A. <u>Advanced Reactor Regulations</u> *The emerging 21st century Advanced Reactors are several orders of magnitude safer than conventional water reactors owing, in part, to the use of passive core decay heat removal features while also employing fuel that cannot catastrophically fail. Conventional water reactors do not possess these inherently fail-safe characteristics.*

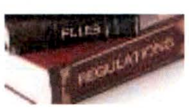
The existing regulatory criteria are clearly based on a tiered approach to nuclear safety, but badly blurred distinctions exist between the highest level of public protection (Safety-Related) and lesser considerations. Confusion and grossly excessive costs inevitably flow from such an exasperating regulatory defect. While the shortcoming may have been somewhat tolerable for conventional reactors, advanced designs should not be burdened by such a poor construct.

The above flaw is easily remedied by minor modifications to Appendix A (General Design Criteria) of Part 50 of the Code of Federal Regulations. Simply clearly differentiate between Safety-Related and lesser requirements. Such an approach also yields a practical method for achieving a graduated regulatory approach to nuclear safety. Such a methodology is being advocated by several advanced reactor developers.

B. <u>General Design Criteria (GDC)</u> *This upper tier regulatory document defines those key elements that all civilian reactors must possess to properly protect the public from undue radiation hazards. The hybrid design complies with all existing GDC requirements. As noted above, clarifications would be helpful to clearly identify key requirements; i.e. "Safety-related" systems, structures and components. However, the hybrid licensing approach can proceed without such changes. By regulation, the applicant must submit the Principal Design Criteria for their design identifying how the applicants design conforms to the GDC. Interestingly, the GDC recognizes that differences may exist and that is acceptable provided proper justification is provided.*

C. <u>NRC Effort</u> *Regulatory efforts should be commiserate with a reactor's inherent level of safety. In the case of most Advanced-Reactors, regulatory activities should be directed primarily at Safety Related features with tiered resources applied to lesser areas. Such self-evident considerations should be inherently contained in the regulatory process, although an Act of Congress may be required to cause the bureaucracy to actually implement the obvious. Further, the NRC management structure needs to be flattened and made consistent with the cost effective methods used in private industry where there is ample recognition of the short-comings of excessive overhead.*

The Hybrid employs Safety-related passive measures for decay heat removal and containment. Also, unlike several many other advanced reactors, the fuel cannot melt. This superior level of safety merits an even more streamlined approach. The significant majority of NRC effort should be devoted to passive Safety-related considerations. While features are helpful in eliminating public radiation exposure, ultimately the passive features are all that are needed to properly protect the public.



D. <u>NRC Staffing</u>. *The NRC review & approval process is based on utilizing large staffs that must be "trained" on the technology being reviewed. Such a process is archaic, bureaucratic, painfully inefficient, and expensive while presuming that scientific and engineering personnel cannot readily understand new technologies.*

Modern energy projects rely on as-needed contracting for the necessary specialty expertise, rather than retaining a large in-house staff that is only intermittently used. A more logical and cost effective approach would adopt a technical Due Diligence model using outside services (preferably private because their costs are much less than government employees). The Due Diligence approach concentrates on uncovering fatal flaws, as opposed tom worrying about items well removed from fundamental considerations – namely the protection the public from hazardous (as in worst case) radiation exposure.

Ideally, NRC staffing would consist of a compact program management team that ultimately provides final recommendations to the NRC Commissioners based on the Due Diligence effort, with the Applicant ultimately responsible for the safety of the public, as opposed to bureaucrats.

E. <u>NRC Costs</u>. *As noted by* **Ref. 35**, *NRC certification costs have increased by a factor of about 4 since the mid 1990's. Expectations for NRC billed costs for the NUSCALE SMR are over $75 million -* **Ref. 36**. *Designer internal costs are estimated at 4 to 5 times that or over $300 million for a net approaching $500 million. Such costs create major burdens on product competitiveness. For instance, at 8% expected return on plant designer's invested equity, over $30 million/year must be covered by future sales. If the objective is to break-even (a poor business proposition) then the development costs must be spread over sales, which may be meager when considering the competitive environment associated with power plant sales.*

F. <u>HYBRID Evacuation Zone</u>. *Conventional reactor evacuation zone 10 miles for a +4400 MW(t) reactor - Grand Gulf Nuclear Plant. Hybrid 630 MW(t), based on reactor sizing alone, zone 630/4400*10 or about 1.4 miles. Conventional reactor core damage frequency is about 10^-05 (see* ***SAFETY: Contrast/*****Risk –Advanced Reactors).** *Hybrid several orders of magnitude safer (Hybrid core damage frequency roughly <10^-08) which very conservatively yields evacuation zone radius of 1.4/10 or 0.14 miles (vice actual calculated 1.4/100 or 0.014 miles). In the interest of more caution, Hybrid evacuation zone set at 1/4th (0.25) mile (125 acres) with site boundary at 1/8 mile (30 acres) and plant area ~6 acres. This simple approach does not fully take into account the fact that the Hybrid's releasable core source terms are much less than a conventional nuclear cores because the Hybrid fuel operates at much lower temperatures (accident <2200°F versus ~4500°F) and a silicone carbide barrier protects the integrity of the fuel particles. As a rule-of-thumb, off-site release frequencies are about an order of magnitude less than core damage frequencies. In other words, core damage does not necessarily lead to off-site radiation releases.*

ADVANCED REACTOR ISSUES

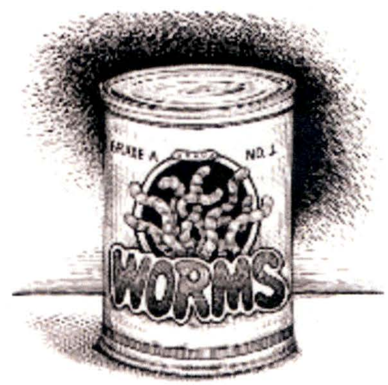
Historical Perspective

The profitability of an enterprise is affected by a myriad of considerations. However, fundamentally the likely reward must be sufficient enough to overcome the perceived downside risks associated with potential failure. In the case of nuclear plants, the potential downside financial risks can be immense which means the potential upside rewards should be substantial. Such a need also means unwarranted financial burdens must be minimized to enhance upside opportunity.

ADVANCED REACTOR ISSUES: *Overview*

FATAL FLAWS

- Financing
- Regulations
  - Roughly $½ Billion "all-in" Cost[1]
- Perceptions



Note: ***(1)*** *See chapter End-note item* **K**

CONCEPT

ADVANCED REACTOR ISSUES : *Development*

Advanced-Reactors

WARD-of-STATE

- ***Return on Investment too Long & too Uncertain for Financial Community***
  - Regulatory Complexity Exacerbates Problem

CONCEPT

ADVANCED REACTOR ISSUES : *Development*

/Funding Models

➢ PUBLIC/PRIVATE COST SHARE[1]

- *Favors Research*
- *Ponderous & Inefficient*
- *Bureaucracy Picks "Winners"[4]*
- *Slows Commercialization*
- *Excludes Small US Businesses[3]*

$ Billions wasted[2]

➢ INVESTOR TAX WRITE-OFFS

✓ *Rapidly Winnows Out Good from Bad[4]*

Not Available

❖ *Needs Legislation*

Notes: *(1) See Chapter End-notes, item **A**. (2) See Chapter End-notes, item **B**. (3) See Chapter End-notes, item **C**. (4) See Chapter End-notes, item **D**. (5) Aim is to confirm technical, commercial & regulatory viability. (6) See Chapter End-notes, item **F**. (7) See Chapter End-notes, item **E**.*

➢ TRADITIONAL

✓ 1st Government Seed Money[5]
- *Innovation Takes Root*

✓ 2nd Tax Write-offs[6]
- *Innovation Grows*

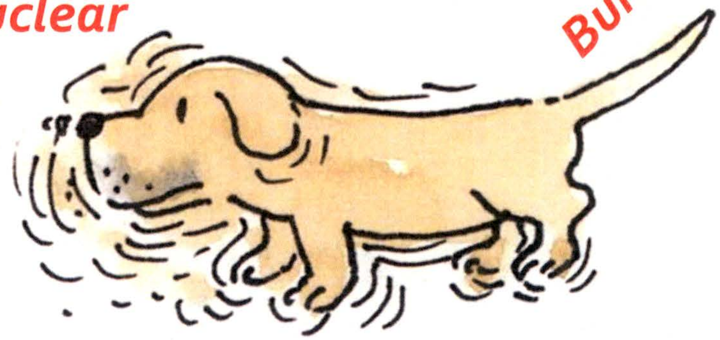
✓ 3rd Commercialization
- *Compete in Marketplace[7]*

Protects Consumer & Taxpayer

CONCEPT

ADVANCED REACTOR ISSUES : *Development* /Licensing

Advanced Nuclear

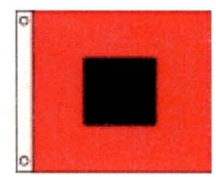


Bureaucracy

EXCESSIVE REGULATIONS

✓ *Why??*

Risk Informed Licensing[1]



"Out-of-the-Pot-into-the-Fire"

POORLY DEFINED REGULATORY SAFETY FUNCTIONS*

- *Drives Requirements*

  Functions Developed for Water Reactors

  // Suited Fit for Passively Safe Advanced Reactors

CONCEPT

Notes: ***(1)*** *See chapter End-notes, item* ***H.***

ADVANCED REACTOR ISSUES : *Over Regulation*

/Safety Functions

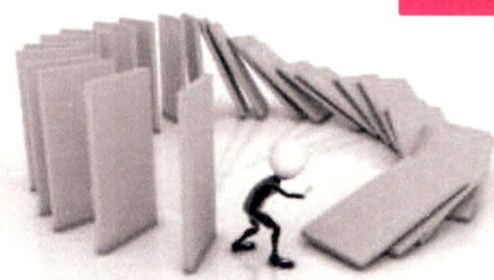
Important-to-Safety[1]
Poorly Defined/Unbounded

Nuclear ?	Personnel ?	Fires ?	Security ?	**Safety-Related** Well Defined & Bounded*

CONFUSING[2]

- *Unintended Consequences*
  - *Overreach, Invariably leads to Excessive Costs*

Oops!



***Safety-Related:** (10CFR 50.2)*
"Those structures, systems and components that are relied upon to remain functional during and following design basis events to insure:
1) The integrity of the reactor coolant boundary;
2) The capability to shutdown the reactor and maintain it in a safe shutdown condition;
3) The capability to prevent or mitigate the consequences of accidents which could result in potential offsite exposures comparable to the applicable guidelines set forth in 50.34 or 100.11"[3]

Note: ***(1)*** *"Important-to-Safety" not defined in Code of Federal Regulations. Applicability thus becomes more-or-less whatever lower-tier regulations believe directly or indirectly impacts safety. Recipe for financial disaster. See chapter End-notes, item* ***A.*** ***(2)*** *As noted by* **Ref. 37** and 10CFR50.63, *"Risk Informed" safety function classifications are emerging but this approach is itself poorly bounded and confusing. See chapter End-notes, item* ***H.*** ***(3)*** *See chapter End-notes item* ***J***

CONCEPT

ADVANCED REACTOR ISSUES : *Over Regulation*
/Quality Assurance

NEEDLESSLY BURDENSOME & EXPENSIVE

- *Design*
- *Construction*
- *Operations*

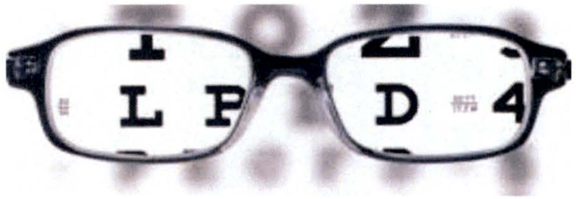
MYOPIC SAFETY FUNCTIONS

- *Unhelpful Paperwork*
- *Inefficient Resource Use*

CONCEPT

<u>Notes</u>: ***(1)*** *See* **Ref.67** *for examples of needless multi-million dollar construction expenditures caused by ill-defined "safety" considerations promulgated by over-regulation.*

ADVANCED REACTOR ISSUES : *Over Regulation*
/Solution



- FOCUS
- LOGIC
- PRECISION

Keep it Simple

~~IMPORTANT to SAFETY~~

NUCLEAR-SAFETY

- *Protect Public from Radiation*

✓ Essential Rules

~~Unnecessary Rules~~

CONCEPT

<u>Notes</u>: *(1) See chapter End-notes, item **I**. (2) See chapter End-notes, item **J**.*

ADVANCED REACTOR ISSUES : *Over Regulation*

/Solution

- **MEETS LAW**[3]
  - ✓ *Logical*
  - ✓ EXISTING REGULATIONS OK, TOO MANY RULES
- **Keep it Simple**
- **PREDICTABLE**
  - ✓ *Accountability*
- ***EFFICIENT***
  - ✓ *Cost & Schedule*
- ***WHY ACCEPTABLE?***
  - ✓ ***HYBRID PASSIVELY FAIL-SAFE***[4]
  - *Legacy NRC Approach Obsolete*

NUCLEAR-SAFETY

Tiered Approach[2]		Tiered Approach[1]
NRC Approve	Primary Nuclear-Safety Functions **SAFETY-RELATED** ***Protect Public from Hazardous Radiation***	**HIGHEST QUALITY PROGRAM NQP-1**
NRC Concur	Secondary Nuclear-Safety Functions **Important-to-Safety-Related** ***Protect SAFETY-RELATED Functions***	**High Quality Program NQP-2**
NRC Accept	Tertiary Nuclear-Safety Functions **Nuclear-Waste** ***Protect Public from Undue Radiation***	**Special Quality Program NQP-3**

PLANT-SAFETY

NRC No Objection	Primary Functions ***Supplemental Safety*** ***Protect Reactor Asset***	*Focused Industry Quality System IQS-1*
NRC Minimally Involved	Universal Functions ***General Safety*** ***Protect Personnel & Equipment***	*Industry Quality System IQS-2*

As established in Applicant's PRINCIPAL DESIGN CRITERIA
As required by GENERAL DESIGN CRITERIA[5]

<u>Notes</u>: ***(1)*** *See chapter End-notes, item M.* ***(2)*** *See chapter End-notes, item* ***L.*** ***(3)*** *See Chapter End-notes, item* ***O.*** ***(4)*** *Orders of magnitude safer than convectional reactors – see* **SAFETY; *Contrast*/Risk** **(5)** See Appendix G

CONCEPT

ADVANCED REACTOR ISSUES : *Over Regulation*

/Solution[1]

Passive Systems

Primary Nuclear-Safety Functions
SAFETY-RELATED (SR)

- Pressure Boundary
- Reactor Shutdown & Decay Heat Removal
- Low Voltage Electrical

Protect Public from Hazardous Radiation

Secondary Nuclear-Safety Functions
Important-to-Safety-Related (ISR)

- Structures & Supports
- Limits[2]
- Fire Protection[3]
- Security[4]

Protect SAFETY-RELATED Functions

Tertiary Nuclear-Safety Functions
Nuclear-Waste (NW-

- Vessels & Piping
- Limits

Protect Public from Undue Radiation

NUCLEAR SAFETY

MAJOR SAVINGS[5]

- *+$140 Million ~40%*

Active Systems

Plant-Safety Top Tier Functions
Supplemental-Safety (SS)

- Core Shutdown & Heat Removal
- Electrical Power & Control
- Structures / Supports

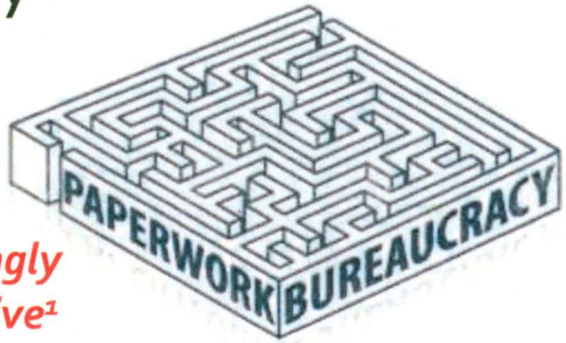
Protect Reactor Asset – avoid fuel overheating

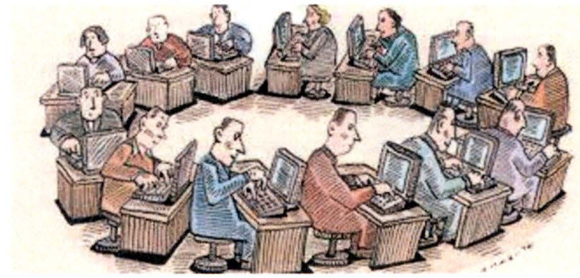
PLANT SAFETY

Notes: ***(1)*** *See* **Appendix B** *for sample safety classification listing, including seismic capabilities.* ***(2)*** *For instance, fuel temperature ceiling during limiting abnormal plant operations, Technical Specifications (operational limits).* ***(3)*** *Reactor Block only, includes fire detection, mitigation & suppression systems – (all powered by essential electrical supply).* ***(4)*** *Reactor Block only (all powered by essential electrical system).* ***(5)*** *See chapter End-notes, item* ***K***.

CONCEPT

ADVANCED REACTOR ISSUES : *Over Regulation* /Bureaucracy





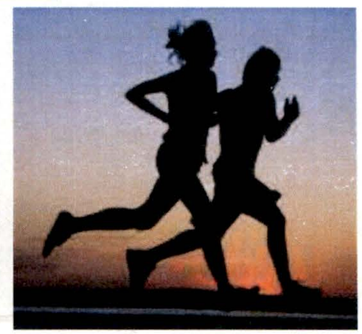
Stunningly Expensive[1]

➢ MUST DO BETTER

- ✓ *Lean Due Diligence Project Model*
  - *Main Focus: Nuclear Safety*
- ✓ *Cast-of-Thousands Unneeded*[2]
  - *Complex Issues? Outside Experts*

Only Requires Administrative Changes,

Modernize



➢ *WHY ACCEPTABLE?*

✓ ***HYBRID PASSIVELY FAIL-SAFE***

- *Legacy NRC Approach Obsolete*

Reform Excessive Review Costs

- *Salary + Benefits*
- *Management: ~15 to 20% of Effort*
- *Agency Overhead: Congressional Budget*

CONCEPT

Notes: *(1) See Chapter End-notes, items* **G** *&* **K.** *(2) See* **Licensing** *Chapter end-note, item* **D***.*

ADVANCED REACTOR ISSUES : *Strategic Threat*

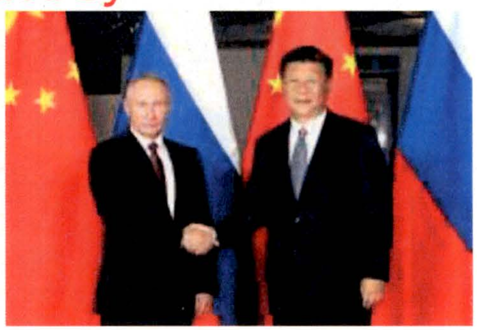
DANGER

If KEY "FATAL-FLAWS"
(Over-Regulation & Financing)
NOT RESOLVED
ADVANCED REACTORS WILL
NOT BE DEPLOYED in US By US FIRMS

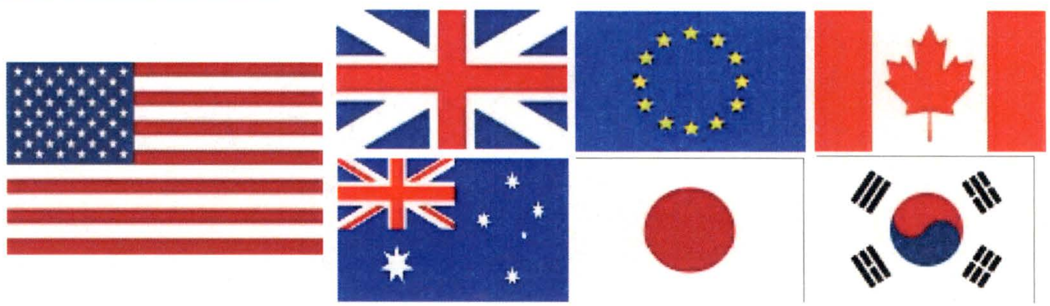
More Likely Supplied By

- ***Russia***
- ***China***

UNWISE



DEPLOY HYBRID
PROTECTS FUTURE GENERATIONS



CONCEPT

ADVANCED REACTOR ISSUES : *Last Fatal Flaw*

PUBLIC FEARS RADIATION

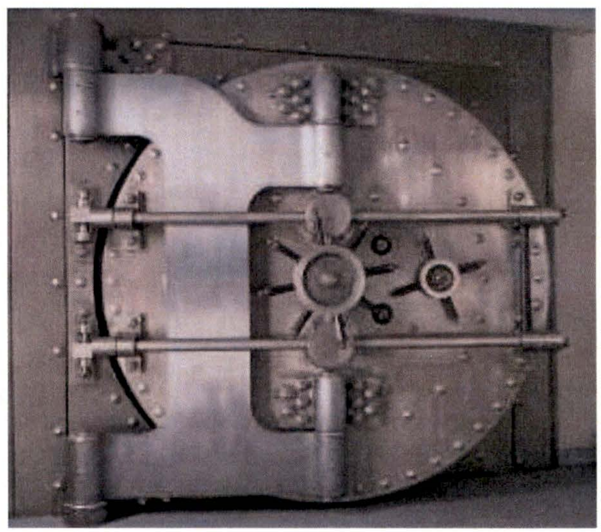
- *May be somewhat illogical, but is a fact.*

Although not entirely without cause.

MAKE SURE NONE GETS LOOSE

✓ *HYBRID PASSIVELY FAIL-SAFE*

- *No Radiation Escapes*



CONCEPT

ADVANCED REACTOR ISSUES: *End-notes*

A. ***<u>Cost Share Model</u>***. *Completely lacks the "checks & balances" normally found in other federal procurement processes. Hundreds of millions of dollars can be (and are) awarded to a single company with no bid process recourse. Absolutely invites abuse – i.e. "Crony Capitalism".*

B. ***<u>Current Model Failure</u>***. *Billions of dollars (public & private) have been expended over the last 20+ years on advanced reactor research & development with virtually no successes. There is an inherent and fundamental flaw in the DOE organization which is primarily composed of academics and bureaucrats with little incentive to ever actually complete an undertaking that leads to commercial success. A better approach is unquestionably needed.*

C. ***<u>Small Business Discrimination</u>***. *The current "Public/Private" model requires a 20% or more cost-share. While perhaps somewhat palatable for large firms with revenue sources from other activities, the requirement is utterly financially fatal for small businesses, the engine of innovation in the US.*

The source of the cost share requirement is the 2005 Energy Act. However, this same act allows the Secretary of Energy to waive the cost-share requirement. Curiously, the DOE habitually ignores this flexibility provided by Congress.

D. ***<u>Picking Winners/Losers</u>***. *Marketplace forces are vastly superior to the government in rapidly picking the winners and losers in the competitive arena. Further, leaving the decision solely to bureaucrats invariably leads to corruption.*

E. ***<u>Power Market Subsidies</u>***. *Selectively applied government subsidies for a particular form of power generation are highly disruptive to the marketplace because the consumer invariably pays excessive prices to unfairly benefit a particular firm or group of investors whose product is uncompetitive. Further, the actual low-cost suppliers are financially penalized – see* **Financial** *chapter, Power Price and Green Energy Fee. If some form of government support is to be provided, then basic fair-play requires subsidies be even handedly applied. For instance, accelerated depreciation for all capital investments associated with building power production facilities.*

F. ***<u>Investment Tax Credits</u>***. *In order to successfully develop advanced-reactors in the US, a rationale inducement is required to unlock private investment, otherwise these energy sources will originate from foreign countries - most likely China or Russia, neither of whom are US friends. The envisioned stimulus is a limited term (say 10 years per specific application) tax credit for investors, designers and manufacturers engaged in the development of advanced reactors.*

G. ***<u>Costs</u>***. *In addition to organizational inefficiencies, the NRC fees (+$270 /hour per 10CFR170) are out-of-line with private industry due to excessive & unrestrained overheads. Only direct personnel costs should be charged (indirect organizational costs funded by Congress) and management activities limited to < 20% of the effort, consistent with private industry. Such a "Checks-&-Balances" approach would be equitable to all parties.*

CONCEPT

ADVANCED REACTOR ISSUES: *End-notes*

***H. <u>Risk-Informed Licensing</u>**. As noted by **Ref. 36,** both the nuclear industry and the NRC are attempting to "simplify" the licensing process though a "risk-informed" philosophy whereby the NRC (in their own words, as stated on the NRC website - see their Risk Assessment/Concepts explanation).*

- *Considers a wide variety of accidents.*
- *Prioritizes accidents based on public safety, operating experience and/or engineering judgement.*
- *Considers every reasonable method to prevent or mitigate an accident.*
- *Highlights areas that are not thoroughly understood.*
- *Tests the sensitivity of analysis results to key assumptions.*

Unclear why NRC is designing plant

Such a regulatory approach must necessarily extend deeply into all facets of plant design, construction, and operation. The complex, confusing, and unbounded nature of these NRC activities inevitably leads to extensive regulatory overreach – this helps explains why licensing costs have so dramatically ballooned (by a factor of 4), as documented by **Ref. 35** *. The "risk-informed" approach generates numerous opportunities to inflict undue costs on all parties.*

***I. <u>Hybrid Licensing</u>**. The Hybrid approach relies on simple rules that mechanistically prioritize nuclear safety functions into discrete manageable groups with well-defined boundaries and requirements. This straightforward approach is justified since public radiation exposure is effectively zero because: (a) the fuel cannot melt; (b) multiple safety-related passive cooling measures prevent fuel damage; and (c) multiple safety-related passive barriers stop radiation releases. There is no logical reason for the NRC to delve deeply into all elements of the Hybrid's design, construction and operation. Stated somewhat differently, as the worst case accidents/events do not adversely impact public safety, there is no sound reason to unleash in-depth regulatory scrutiny into lesser events well removed from affecting the public. In the case of conventional reactors, active measures (electrical power & water) are required to avoid undue adverse public safety impacts. Not surprising that the regulatory process is inherently more involved and cumbersome than necessary for passively fail-safe advanced reactors.*

***J. <u>Public Radiation Exposure</u>**. The top-tier codified (10CFR50.34 & 100.11) accident related, radiation exposure limit for the public is essentially 25 REM. However, the NRC favors lower tier regulatory safety goals that cast exposure acceptability in terms of probabilities -* **Ref. 37**. *These goals are clearly a form of ill-defined regulatory ratcheting when considering the inherent difficulties in attempting to quantify acceptance criteria involving both accident probabilities and latent deaths predictions. Properly, the Code of Federal Regulations should be modified if new exposure limits are collectively considered necessary, as opposed to unilateral bureaucratic actions.*

CONCEPT

ADVANCED REACTOR ISSUES: *End-notes*

K. Licensing Savings*. As noted in the* **Licensing** *chapter End-note* **E***, the expected baseline all-in cost to obtain a design certification is nearly $400 million over an 8 year period. This figure excludes plant Owner licensing costs.*

Relative to conventional reactors, the passively fail-safe Hybrid involves: ~50% fewer sub-tier regulations; ~60% fewer accidents/events; ~75% fewer highly regulated components. Collectively we are of the opinion that the current 8 year certification period can be reduced to about 5 years. This translates to NRC licensing billed costs of about $50 million with private expenditures of about $190 million -- "all-in" cost of about $240 million (net savings of over $140 million or nearly 40%). If DOE provides 50% help, private investment would be $120 million.

If NRC overhead costs were fully shifted to Congressional appropriations, as recommended earlier, the NRC costs billed to private industry would be further reduced to about $30 million (~35% additional savings).

The Hybrid approach will also reduce construction time frames and costs. These expectations are factored into the cost estimates of the **Financial** *chapter. Operational savings would also occur, but have not been quantified. These savings involve more efficient work with overly expansive and time consuming assurance measures scaled back to reasonable proportions.*

L. NRC Reviews*. In the context of the Hybrid licensing program, the following are proposed:*

- ***"NRC Approve"****: means rigorous independent validation, as deemed appropriate by NRC, that applicant has convincingly demonstrated that the Safety-Related functions will be fulfilled for the plant's limiting design basis events.*
- ***"NRC Concur"****: means reaching a sound conclusion that applicant has demonstrated that Important-to-Safety-Related protective functions are fulfilled for the plant's limiting design basis events. This would include defined and bounded audits of select applicant activities, as considered appropriate considering function's nuclear safety significance.*
- ***"NRC Accept":*** *means overview conclusion that applicant's Nuclear-Waste functions can be reasonably accomplished.*
- ***"NRC No Objection"****: means an overview assessment that applicant's Supplemental-Safety functions can be reasonably accomplished.*

M. Quality Programs*. Tiered approach, as clearly allowed under Criterion 1 of the General Design Criteria, 10CFR50*

O. Compliance with Law*. Per 10CFR50: "These General Design Criteria establish minimum requirements for the principal design criteria for water-cooled nuclear power plants similar in design and location to plants for which construction permits have been issued by the Commission. The General Design Criteria are also considered to be generally applicable to other types of nuclear power units and are intended to provide guidance in establishing the principal design criteria for such other units" The Hybrid employs more precision in defining "Important-to-Safety" and readily meets the intent of the General Design Criteria, as implemented by the Principal Design Criteria for the Hybrid.*

CONCEPT

STATUS

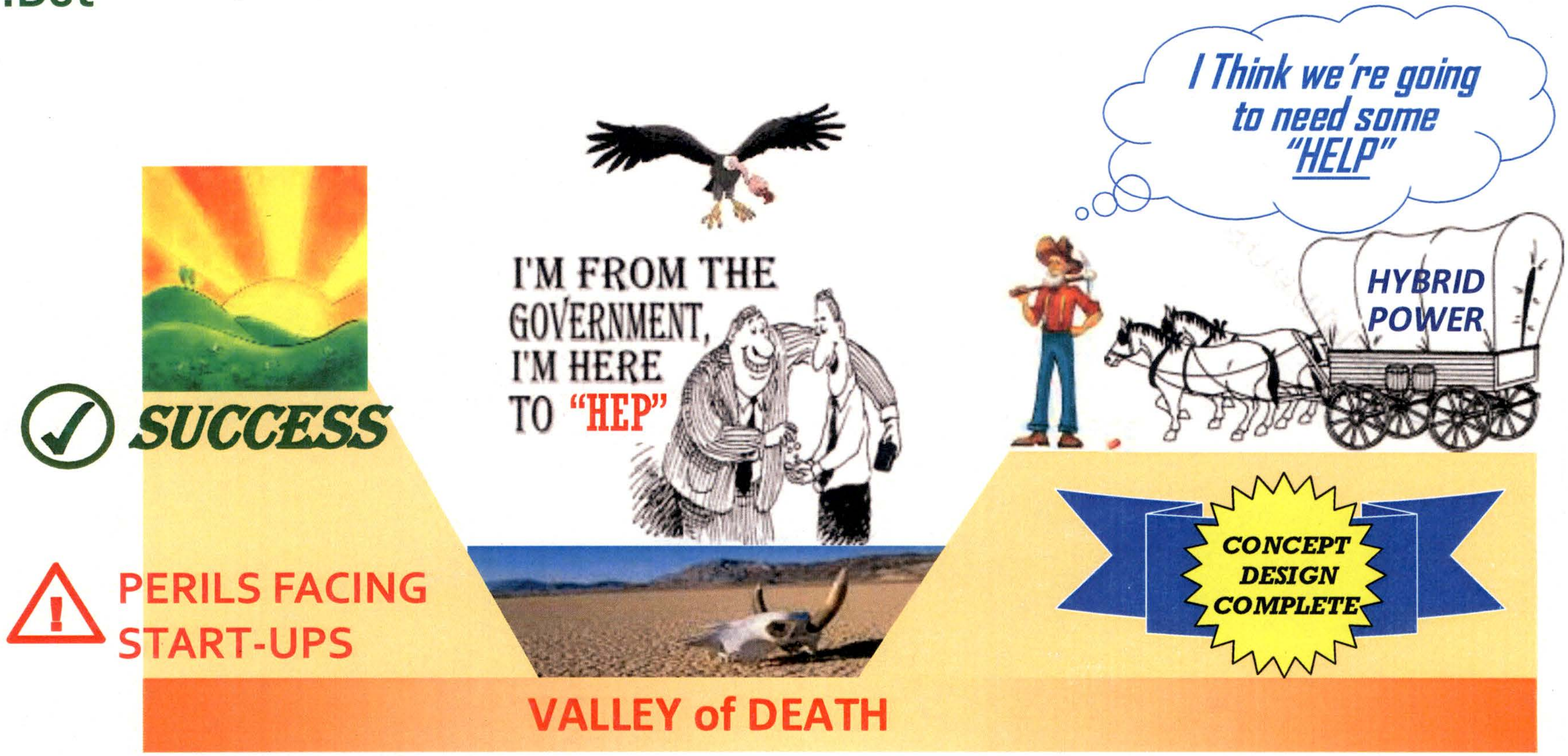
Historical Perspective

The time frame for sustained initial deployment of power industry technologies has generally been on the order of a decade. Conventional reactors and gas turbines are now in year 60 of their lifecycle while coal plants have moved past the century mark.

While modern design and manufacturing techniques are accelerating the development of new technologies, excessive government regulations can have the opposite effect, significantly lengthening the time for new products to enter the marketplace. Unnecessary regulatory delays and requirements can also increase the cost of new technologies to the point where the machines may not be commercially viable in the country of origin and are thus subsequently manufactured and deployed by overseas competitors.

STATUS: *Poised to Move Ahead*

/ ...But



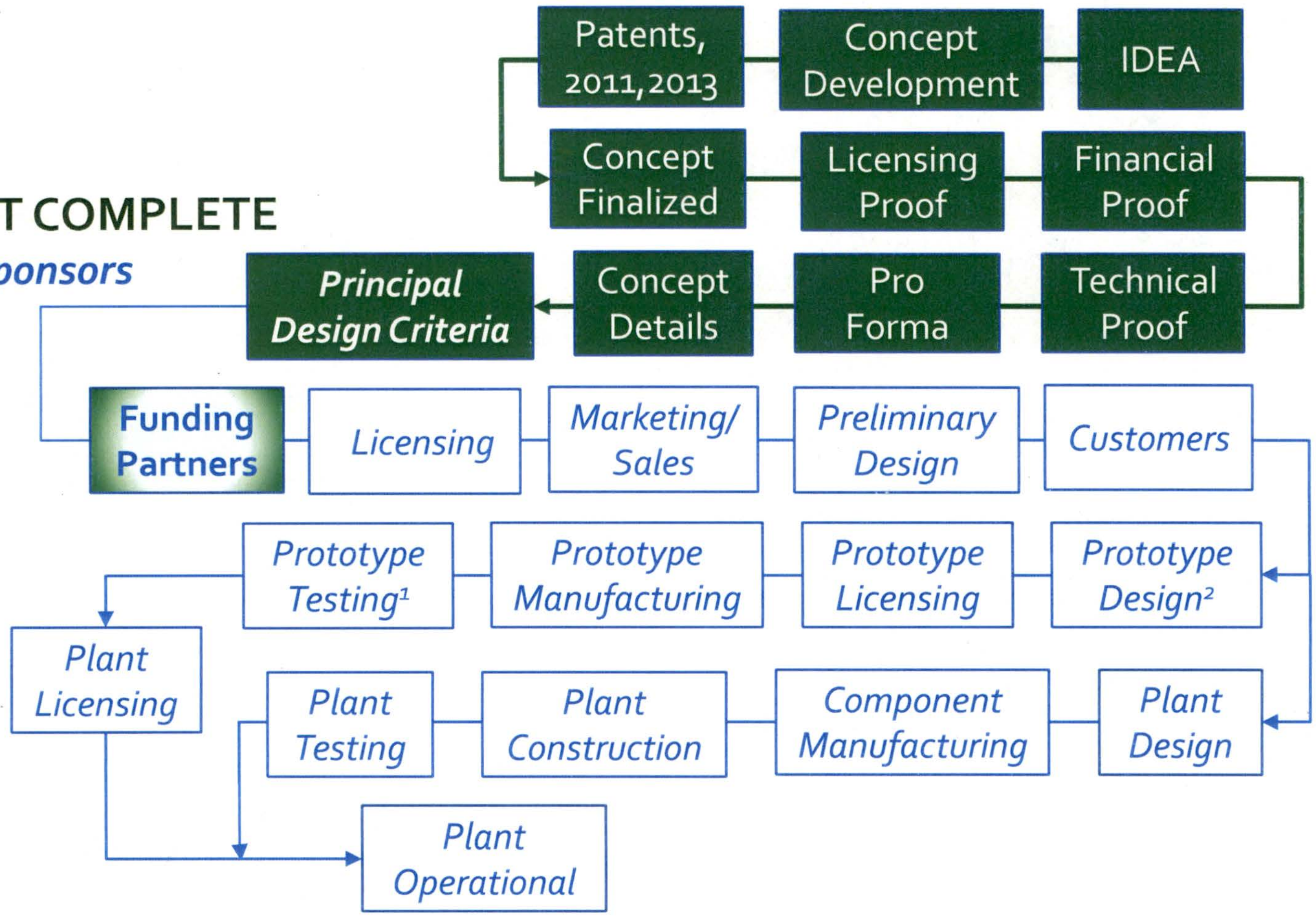
- THUS FAR, PRIVATELY FINANCED
  - ✓ *US Small Business Innovation at Work.*
  - ✓ *US Government ... All Assistance Well Short of Actual Help.*

CONCEPT

STATUS: *Path Forward* /Simplified

➢CONCEPT COMPLETE

✓*Attract Sponsors*



Notes: ***(1)*** *Initial nuclear fuel testing envisioned to occur at existing prototype gas reactor in Japan (HTTR). Rotating machinery prototype testing traditionally occurs at manufacturing facilities.* ***(2)*** *Prototype Hybrid/All-Nuclear power plant to confirm reactor technology characteristics in of support future full Hybrid/Gas & Coal Gas production plants. The reactor block is considered the largest risk factor, by a large margin*

CONCEPT

CONCLUSION

Historical Perspective

The quest to provide electrical energy has invariably entailed complicated tradeoffs involving:

- *Environmental Impacts*
- *Profitability versus Consumer Costs*
- *Regulations*
- *Health and Safety*
- *Suitable Technologies*
- *Public versus Private ownership.*
- *Government supports and subsidies*

However evolving compromises were reached with recognition that modern civilization can only exist if abundant, reasonably priced, and reasonably clean electrical energy is available.

CONCLUSION: *Summary*

✓ MUCH BETTER[1]

- FAIL-SAFE
- PRACTICAL
- VERSATILE
- GOOD VALUE
- ECO FRIENDLY

CONCEPT

Note: ***(1)*** *Policy summaries, see chapter End-notes*

CONCLUSION: *Summary*

➢ **HYBRID PROTECTS**

CONCEPT

CONCLUSION: *Rankings*

/Nuclear Plants

Categories[1]	HYBRID	*Gas Reactors*	*Water Reactors*
Uses	★	✗+	✗
Financial	★	✗+	✗
Environment	★	✓	✗
Safety	★	✓	✗
License	✓+	✗+	✗+
Technical	✓+	✗+	✗+
NET[2]	✓+	✗+	✗

★ = *Best,* ✓ = *Average,* ✗ = *Needs Work.*

- ➢ HYBRID GOOD
  - ✓ Most Able Technology

Notes: ***(1)*** *Scoring relative to each other.* ***(2)*** *Average of categories.*

CONCEPT

CONCLUSION: *Rankings*

/Power Plants[1]

Category[2]	HYBRID	*Gas*	*Wind & Solar[4]*	*Coal*	*Nuclear*
Uses	★	✓	✗	✓	✗+
Environment	★	✓+	✗+	✗	✗+
Financial	★	✓+	✗	✗+	✗
Technical	✓+	★	✓	✓	✗
Safety	★	★-	✓-	✓-	✓-
License	✓	★	✓	✗	✓
NET[3]	★-	✓+	✗+	✗+	✗+
	VERY GOOD	*GOOD*	*Very Low*	*Very Low*	*Poor*

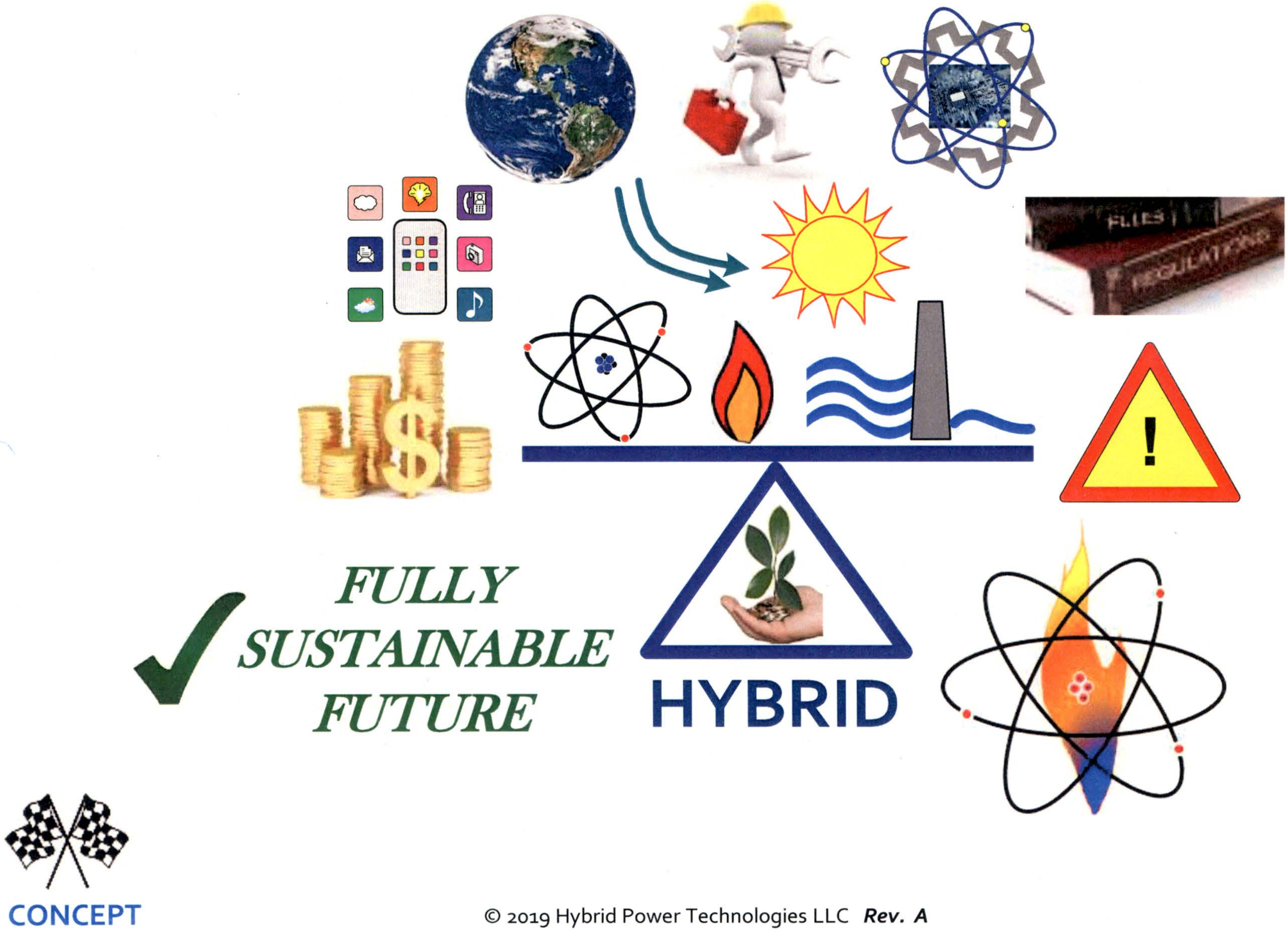
★ = *Best,* ✓ = *Average,* ✗ = *Needs Work. See* **Appendix A** *for ranking method*

- ➢ HYBRID MOST VERSATILE & CAPABLE
  - ✓ Best for Planet & Future Generations

Notes: ***(1)*** *See chapter End-notes item* ***A*** *for energy policy ramifications.* ***(2)*** *Rankings from earlier chapters, normalized.* ***(3)*** *Relative to each other.* ***(4)*** *Best use is peaking and distributed generation, not base-load or load following.*

CONCEPT

CONCLUSION: Better World
/Right-Energy-in-Right-Place



CONCLUSION: *End-Notes*

- ***ENERGY & CLIMATE-CHANGE POLICY***

World energy policies are based on act-of-faith belief that man-made CO_2 emissions are dangerous. Governments dictate spending $ trillions on "green" energy while moving massive sums of wealth from the planet's poor & middle-class to the well-connected and undeserving few.

Better Strategy: Deploy Hybrid

The hybrid side-steps the contentious CO_2 conflict. Regardless of whether or not CO_2 is a real or imagined problem, significant CO_2 emission reductions occur while providing future generations with reasonably priced, safe, environmentally sound, and unlimited sustainable energy.

All energy resources (fossil, nuclear, renewable) are used wisely.

- ***REGULATORY POLICY***

Current nuclear regulations are needlessly overly prescriptive for advanced reactors and ultimately ruinous to energy independence as well as the environment.

Better Strategy:

1. ***Focus regulatory efforts on Nuclear Safety (chiefly Safety-Related).***
2. ***Use compact & streamlined NRC "Due Diligence" organization.***

The Hybrid's superior ability to protect public easily supports such a cost-effective approach.

- ***GOVERNMENT SUPPORT POLICY***

Sole reliance on government funding is strategically and financially unwise as well as counter-productive while stifling innovation & marketplace efficiency.

Better Strategy: Use Investment Community. *Incentivize Advanced-reactor development using tax credits/write-offs for venture capitalists, small businesses, designers & manufacturers.*

The Hybrid is an example of US small business innovation solving seemingly intractable problems. The Hybrid concept was developed with no government assistance.

CONCEPT

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CONCEPT

CREDENTIALS: *Biography*
/Michael F. Keller

Mr. Keller is a +45 year veteran of the power industry, and has worked for a nuclear shipbuilder, reactor manufacturer, utilities, engineering firms and consultants. Mr. Keller is the President of Hybrid Power Technologies, LLC.

Management responsibilities included a broad range of activities: power plant daily operations; capital budgeting; power sales; regulatory compliance; health and safety; emergency planning; financial Pro Forma analysis; loss prevention; plant/process engineering; scheduling; human resources; facility management; strategic planning; business development. Directed, managed, and supervised multi-discipline teams of engineering, craft, and operations personnel engaged in the design, construction, start-up, operation, and repair of power plants. Plant Manager, Outage Manager, Engineering Manager, Project Manager & Director

Extensive engineering, business, management, and operations experience involving all types of power plants, including: combined-cycle; pulverized, stoker and fluid bed coal boilers; simple cycle combustion turbines; nuclear; gas fired boilers; and diesels. Process plant experience includes hydrogen production facilities.

"Hands-on" operational experience includes: reactors, turbines, generators, boilers, switchyards, emissions control equipment; steam systems, bulk handling systems; waste and water treatment; cooling towers; plant control systems; electrical high voltage and distribution systems; piping, civil, structural and geotechnical.

Professional:

Professional Engineer: Kansas #14158.; Member ASME; Senior Reactor Operator Site Certificate.

US Patents: 7,961,835; 8,537,961 & others under development.

Education:

Bachelor of Science, Nuclear Engineering, *University of Virginia*, 1972

Master of Science, Mechanical Engineering, *Rensselaer Polytechnic Institute,* 1979

Masters Business Administration, *St. Martin's College,* 1986

CREDENTIALS: *Papers & Lectures*

A. Conference Presentations & Publications

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APPENDIX A: *Ranking* /Methodology

Where ever possible, rankings are developed from quantitative comparison data contained within the report. An initial ranking is made using the data *range* and an *interval* equal to the *range* divided by three.

High	High -	Average+	Average	Average-	Lowest+	Lowest
Best	High minus 0.2 x Interval	Average plus 0.6 x Interval	(Best plus Worst) / 2	Average minus 0.2 x Interval	Lowest plus 0.6 x Interval	Worst

The above is transposed into the following standardized scoring system.

GOOD	High -	Average+	Average	Average-	Lowest+	Lowest
1.0	1.13	1.6	2.0	2.13	2.6	3.0
☆	☆-	✓+	✓	✓-	✗+	✗
Very Good	Good	Better	Adequate	Improve	Marginal	Needs Work

CONCEPT

APPENDIX B: *Safety Classes*

/Summary – *Table Abbreviations*

NUCLEAR SAFETY							
SR = Safety Related	PB = Pressure Boundary	SD = Reactor Shutdown	DH = Decay Heat Removal	LVE= Low Voltage Electrical			
ISR = Important-to-Safety-Related	pPB = Protect Pressure Boundary	pSD = Protect Reactor Shutdown	pDH = Protect Decay Heat Removal	pLVE- Protect Low Voltage Electrical	pL = Protect Limits	pF = Protect Fires	pS = Protect Security
PLANT SAFETY							
SS = Supplemental Saftey	sb = Supports & Boundaries	sd = Reactor Shutdown	dh = Decay Heat Removal	ec = Electrical Control	ep = Electrical Power		
GS = General Safety	P = Personnel	E = Electrical	F = Fires	HE = High Energy	S = Security	R = Radiation	

PROGRAM	QUALITY ASSURANCE SUMMARY
NQP-1	Top tier Nuclear quality program in accordance with Appendix B of the Code of Federal Regulations . Used with systems, structures, and components designated as Safety-Related.
NQP-2	Second tier Nuclear quality program employing select elements of NQP-1 and used with Important-to-Safety-Related systems. structures, and components. Quality elements commiserate with importance to protecting Safety-related function.
NQP-3	Third tier Nuclear quality program employed with items involved with nuclear waste
PQS-1	Plant quality system based on augmented industrial measures and used with items designated as Supplemental Safety.
PQS-2	Plant quality system used with general production equipment and systems.

ID	ORGANIZATION	ID	ORGANIZATION
ACI	American Concrete Institute	IEEE	Institute of Electrical & Electronics Engineers
AISC	American Institute of Steel Construction		
ASME	American Society of Mechanical Engineers		

SEISMIC CATEGORY	REQUIREMENT
1	Remain operational during design earthquake.
1A	Remain operational after design earthquake
1B	Remain functional after design earthquake.
2	Industry standard capability.

CONCEPT

APPENDIX B: *Safety Classes*

/Summary

SYSTEMS, STRUCTURE, COMPONENTS	SAFETY CLASS	SEISMIC CLASS	TYPICAL CODE	QA PROGRAM
1. Core System				
A. Fuel Blocks	ISR-pDH	1A	ASME III – Div. 5	NQP-2
B. Fuel Sleeves	ISR-pDH	1A	Manufacturer	NQP-2
C. Fuel Pellets				
1) Outer Coating	ISR-pPB	1A	Manufacturer	NQP-2
2) Carbon Matrix	ISR-dh	1A	Manufacturer	NQP-2
D. Fuel Kernel				
1) Outer Coating	SR-PB	1	Manufacturer	NQP-1
2) Inner Coatings	ISR-pPB	1A	Manufacturer	NQP-2
3) Carbon Matrix	ISR-pPB	1A	Manufacturer	NQP-2
4) Fuel Particle	ISR-pPB	1A	Manufacturer	NQP-2
E. Moderator Blocks	ISR-dh	1A	ASME III – Div. 5	NQP-2
F. Control Rod Blocks	SR-SD	1A	ASME III – Div. 5	NQP-1
G. Trip Rods	SR-SD	1	ASME III – Div. 5	NQP-1
1) Housings	SR-PB	1	ASME III – Div. 5	NQA-1
H. Trip Pellets, & Linkage	SR-SD	1A	ASME III – Div. 5	NQP-1
1) Internal Housing	SR-PB	1A	ASME III – Div. 5	NQP-1
I. Maneuvering Rods & Drives	SS-sd	1B	ASME III – Div. 5	PQS-1
1) External Housing	SR-PB	1	ASME III – Div. 5	NQP-1
1) Internal Housing	ISR-pPB	1A	ASME III – Div. 5	NQP-2

CONCEPT

APPENDIX B: *Safety Classes*
/Summary

SYSTEMS, STRUCTURE, COMPONENTS	SAFETY CLASS	SEISMIC CLASS	TYPICAL CODE	QA PROGRAM
2. Reactor System				
A. Vessel	**SR-PB & DH**	**1**	**ASME III – Div. 5**	**NQP-1**
1) Supports	**ISR-pPB**	**1A**	ASME III – Div. 5	**NQP-2**
2) Foundation	**ISR-pPB**	**1A**	ACI, AISC	**NQP-2**
B. Shroud	**ISR-pDH**	**1B**	ASME VIII	**NQP-2**
1) Supports	**ISR-pPB**	**1B**	ASME VIII	**NQP-2**
C. Barrel	**ISR-pDH**	**1B**	ASME VIII	**NQP-2**
3. Interconnecting Legs				
A. Outer Leg Vessels	**SR-PB**	**1**	ASME III – Div. 5	**NQP-1**
1) Supports	**ISR-pPB**	**1A**	ASME III – Div. 5	**NQP-2**
2) Foundation	**ISR-pPB**	**1A**	ACI, AISC	**NQP-2**
B. Inner Leg Piping	**SS-sb**	**1B**	ASME VIII	**PQS-1**
1) Supports	**SS-sb**	**1B**	ASME VIII	**PQS-1**
C. Helium Coolant	**SS-dh**	**1A**		**PQS-1**

APPENDIX B: *Safety Classes*
/Summary

SYSTEMS, STRUCTURE, COMPONENTS	SAFETY CLASS	SEISMIC CLASS	TYPICAL CODE	QA PROGRAM
4. He Turbine/Compressor				
a. Outer Vessel	SR-PB	1	ASME III – Div. 5	NQP-1
1) Supports	ISR-pPB	1A	ASME III – Div. 5	NQP-2
2) Foundation	ISR-pPB	1A	ACI, AISC	NQP-2
b. Inner Vessel	SS-dh	1B	ASME VIII	PQS-1
1) Supports	SS-dh	1B	ASME VIII	PQS-1
c. Machinery	SS-dh	2	Manufacturer	PQS-1
5. Pre-Heater & Pre-Cooler				
a. Outer Vessels	SR-PB	1	ASME III – Div. 5	NQP-1
1) Supports	ISR-pPB	1A	ASME III – Div. 5	NQP-2
2) Foundation	ISR-pPB	1A	ACI, AISC	NQP-2
b. Inner Vessel	SS-sb	1B	ASME VIII	PQS-1
1) Supports	SS-sb	1B	ASME VIII	PQS-1
2) Internals	SS-dh	1B	ASME VIII	PQS-1

CONCEPT

APPENDIX B: *Safety Classes*

/Summary

SYSTEMS, STRUCTURE, COMPONENTS	SAFETY CLASS	SEISMIC CLASS	TYPICAL CODE	QA PROGRAM
6. Essential Power System				
a. Diesel	SS-ep	1B	IEEE	PQS-1
1) Foundation	SS-ep	1B	AIC, AISC	PQS-1
b. Switchgear & Equipment	SS-ep	1B	IEEE	PQS-1
2) Foundation	SS-ep	1B	AIC, AISC	PQS-1
c. Cables	SS-ep	1B	IEEE	PQS-1
d. Batteries	SS-ep	1B	IEEE	PQS-1
7. Vital Power System (Low voltage)				
a. Equipment	SR-EP	1	IEEE	NQP-1
1) Foundation	ISR-pEP	1A	AISC	NQP-2
b. Cables	SR-EP	1	IEEE	NQP-1
c. Batteries	SR-EP	1	IEEE	NQP-1
8. Reactor Protection System (low voltage)				
a. Equipment	SR-EC	1	IEEE	NQP-1
1) Foundation	ISR-pEC	1A	AIC, AISC	NQP-2
b. Cables	SR-EC	1	IEEE	NQP-1
c. Batteries	SR-EC	1	IEEE	NQP-1
9. Plant Electrical Systems - general	GS	2	IEEE	PQS-2

CONCEPT

APPENDIX B: *Safety Classes*

/Summary

SYSTEMS, STRUCTURE, COMPONENTS	SAFETY CLASS	SEISMIC CLASS	TYPICAL CODE	QA PROGRAM
10. Containment Building				
A. Vessel	SR-PB & DH	1	ASME III, MC	NQP-1
1) Supports	ISR-pPB, pDH	1A	ASME III, Div 5	NQP-2
2) Foundation	ISR-pPB, pDH	1A	ACI, AISC	NQP-2
11. Outer Shield Building				
A. Structure	ISR-pPB, pDH	1A	AISC	NQP-2
1) Foundation	ISR-pPB	1B	AIC, AISC	NQP-2
12. Inner Shield Building				
A. Structure	ISR-pDH	1A	AIC, AISC	NQA-2
1) Foundation	ISR-pDH	1B	AIC, AISC	NQA-2
13. Reactor Auxiliary Building				
A. Structure	SS-sb	1B	AIC, AISC	PQS-1
1) Foundation	SS-sb	1B	AIC, AISC	PQS-1
15. Block & Sleeve Storage				
A. Canisters	SR-PB	1	AISC	NQA-1
1) Racks	ISR-pPB	1A	AISC	NQP-2
B. Structure	ISR-pDH	1A	AIC, AISC	NQP-2
1) Foundation	ISR-sb	1B	AIC, AISC	NQP-2

CONCEPT

APPENDIX C: *Emissions*

Table C-1 Sulfur Emissions

Parameter	Coal [2]	Coal-Gas [2]	HYBRID/ COAL-GAS [6]	Gas [5]	HYBRID/ GAS [6]
Net Output, MW	530	635	1050	501	975
Efficiency, HHV **(fossil fuel use)**	36.6%	41.1%	78%	55.6%	83%
Fossil Fuel [1] Lbm/MWh (net)	750	540	285	270	181
Sulfur In, Lbm/MWh (net)	22	18	8	0	0
Sulfur Out, Lbm/MWh (net)	0.71	0.105	0.049	0	0
EPA Limit [3] Lbm/MWh (net)	1.4	1.4	1.4	1.4	1.4
Compliance?	Yes	Yes	Yes	Yes	Yes
Pending EPA Limit [4] Lbm/MWh (Net)	0.4	0.4	0.4	0.4	0.4
Compliance? (% of Limit)	No (177%)	Yes (26%)	Yes (12%)	Yes (0%)	Yes (0%)

Table Notes: ***(1)*** *US Illinois coal, 13,000 MMBTU/Lbm Dry, 2.8% Sulfur.* ***(2)*** *Coal and Coal-gas (Shell IGCC) plant characteristics –* **Ref. 20**. ***(3)*** *New Source Performance Standards, 2005, ~94% reduction.* ***(4)*** *National Emission Standards for Hazardous Air Pollutants, 40CFR Parts 60 & 63, ~98% reduction.* ***(5)*** *General Electric (GE) 7HA.02 Performance data, circa 2017.* ***(6)*** *Hybrid calculated values.*

CONCEPT

Table C-2
Particulate Emissions

Parameter	Coal[2]	Coal-Gas[2]	HYBRID/ COAL-GAS[6]	Gas[5]	HYBRID/ GAS[6]
Net Output MW	530	635	1050	501	975
Efficiency HHV **(fossil fuel use)**	36.6%	41.1%	78%	55.6%	83%
Fossil Fuel[1] Lbm/MWh (net)	750	540	285	270	181
Particulate In Lbm/MWh (net)	64	51	24	0	0
Particulate Out Lbm/MWh (net)	0.112	0.061	0.032	0	0
Particulate Out Lbm/MMBTU (fuel)	0.011	0.0074	0.0038	0	0
EPA Limit[3] Lbm/MMBTU (fuel)	0.015	0.015	0.015	0.015	0.015
Compliance?	Yes	Yes	Yes	Yes	Yes
Pending EPA Limit[4] Lbm/MWh	0.09	0.09	0.09	0.09	0.09
Compliance? (% of Limit)	No (125%)	Yes (68%)	Yes (36%)	Yes (0)%)	Yes (0%)

Table Notes*: **(1)** US Illinois coal, 13,000 MMBTU/Lbm Dry, 6.72 Lbm/MMBTU particulates. **(2)** Coal and Coal-gas (Shell IGCC) plant characteristics –* **Ref. 20***. Hybrid calculated values. **(3)** New Source Performance Standards, 2005, ~99.75% reduction. **(4)** National Emission Standards for Hazardous Air Pollutants, 40CFR Parts 60 & 63, ~99.8% reduction. **(5)** GE &HA.02 performance data, circa 2017. **(6)** Hybrid calculated values.*

CONCEPT

Table C-3
Mercury Emissions

Parameter	Coal[2]	Coal-Gas[2]	HYBRID/ COAL-GAS[6]	Gas[5]	HYBRID/ GAS[6]
Net Output MW	530	635	1050	501	975
Efficiency HHV **(fossil fuel use)**	36.6%	41.1%	78%	55.6%	83%
Fossil Fuel[1] Lbm/MWh (net)	750	540	285	270	181
Mercury In Lbm/MWh (net) x 10^-06	167	133	38	0	0
Mercury Out Lbm/MWh (net) x 10^-06	10	5	1.7	0	0
EPA Limit[3] Lbm/MWh x 10^-06	20	20	20	20	20
Compliance?	Yes	Yes	Yes	Yes	Yes
Pending EPA Limit[4] Lbm/MWh x 10^-06	4	3	3	3	3
Compliance? (% of EPA Limit)	No (250%)	No (167%)	Yes (79%)	Yes (0%)	Yes (0%)

__Table Notes__***:*** ***(1)*** *US Illinois coal, 13,000 MMBTU/Lbm Dry, 0.25 PPM Mercury.* ***(2)*** *Coal and Coal-gas (Shell IGCC) plant characteristics -* **Ref. 20**. ***(3)*** *New Source Performance Standards, 2005, roughly 88% reduction.* ***(4)*** *National Emission Standards for Hazardous Air Pollutants, 40CFR Parts 60 & 63, ~97.6% reduction.* ***(5)*** *GE &HA.02 performance data, circa 2017.* ***(6)*** *Hybrid calculated values.*

CONCEPT

Table C-4
NOx Emissions

Parameter	Coal[2]	Coal-Gas[2]	HYBRID/ COAL-GAS[6]	Gas[5]	HYBRID/ GAS[6]
Net Output MW	530	635	1050	501	975
Efficiency HHV **(fossil fuel use)**	36.6%	41.1%	78%	55.6%	83%
Fossil Fuel[1] Lbm/MWh (net)	750	540	285	270	181
NOx Out Lbm/MWh (net)	0.611	0.486	0.23	0.27	0.16
NOx Out PPM	70	35	30	25	25
EPA Limit[3] Lbm/MWh (net)	1.0	1.0	1.0	1.0	1.0
Compliance? (% of Limit)	Yes (61%)	Yes (49%)	Yes (24%)	Yes (27%)	Yes (16%)
Likely New EPA[4] Lbm/MWh (net)	0.13	0.13	0.13	0.13	0.13
Technology Future Reduction Capability[7]	Low	Limited	Moderate	High	High

<u>**Table Notes**</u>***:*** ***(1)*** *US Illinois coal, 13,000 MMBTU/Lbm Dry.* ***(2)*** *Coal and Coal-gas (Shell IGCC) plant characteristics per* **Ref. 20**. ***(3)*** *New Source Performance Standards, 2005, ~80% reduction.* ***(4)*** *Best guess. Depends on location of plant. No specific new limits have been published by EPA. Becomes issue of reducing overall regional NOx levels.*

<u>Example</u>: Replace 1000 MW Coal plant with Hybrid/Coal-gas, reduces NOx emission by ~4.5 tons per day or ~405 tons per summer season (~40% reduction).

(5) *GE 7HA.02 performance data, circa 2017.* ***(6)*** *Hybrid calculated values.* ***(7)*** *Selective Catalytic Reduction technology (~3 PPM NOx) can be used on all gas turbines, but becomes more expensive with ever more stringent NOx removal requirements.*

CONCEPT

APPENDIX D: *Gas Reactors*

/Operational Helium Units[1]

Table D1: Helium Reactors

NAME	Dragon	AVR	HTTR	HTR	Beach Bottom	THTR	Fort St Vrain
Origin	United Kingdom	Germany	Japan	China	US	Germany	US
Date	1964-1975	1967 to 1988	1998 to Present	2000 to Present	1966 to 1974	1985 to 1991	1976 to 1989
Type	Graphite Block	Graphite Pebble-Bed	Graphite Block	Graphite Pebble-Bed	Graphite Block	Graphite Pebble-Bed	Graphite Block
Temperature	700 °C	>900°C	~950°C	~950°C	~700°C	~750°C	~700°C
Output *Thermal* *Electric*	*20 MW(t)*	*46 MW(t)*	*30 MW(t)*	*10 MW(t)*	*115 MW(t)* *~72 MW(e)*	*750 MW(t)* *~300 MW(e)*	*842 MW(t)* *~330 MW(e)*
Power Generation	*n/a*	*n/a*	*n/a*	*n/a*	*Steam Generator*	*Steam Generator*	*Steam Generator*
Remarks	Test Reactor	Test Reactor	Test Reactor	Test Reactor	Limited Commercial Success	Limited Commercial Success	Commercial Failure[2]

<u>Table Notes</u>: ***(1)*** *In addition to Helium gas reactors, 14 commercial Advanced Gas Reactors have been deployed in Great Britain. These block core gas reactors are CO_2 cooled and use steam generators. The units are considered commercial successes. However, these types of reactors are not suitable for high temperature operations due to adverse CO_2 chemical inter-actions with graphite as well as the fuel's metal cladding (magnesium).* ***(2)*** *Dismal capacity factor and full-power never reached.*

APPENDIX D: *Gas Reactors*

/Past Technical Problems

Table D-2: Technical Problems

ISSUE[1]	HYBRID Solution
A. Reactor vessel not practical. For 24 foot diameter vessel, ASME Code would require +10 inch thick forgings to satisfactorily accommodate required pressures and temperatures using existing nuclear approved materials.	Vessel-in-vessel design allows use of rolled plate made from approved materials. Design includes ***Proprietary*** features . See **TECHNICAL: *Vessels.***
B. Fuel too difficult & expensive to manufacture. Requires drilling hundreds of holes in graphite block. Blocks cannot be re-cycled.	***Proprietary*** block and sleeve design. See **TECHNICAL: *Nuclear Fuel.***
C. US uranium carbide fuel unreliable. Tends to leak and radioactively contaminate reactor systems.	Use well proven German & Japanese uranium oxide design with ***Proprietary*** pellet design features. See **TECHNICAL: *Fuel***
D. Helium rotating machinery not practical. Limitations of earlier design, materials & manufacturing methods.	Modern methods coupled with modern gas turbine designs and materials. ***Proprietary*** machinery design. See **TECHNICAL: *He Turbine-Compressor***.
E. Conventional heat exchangers too inefficient. Intrinsic limitation of shell & tube designs.	Modern compact heat exchangers designs, modern materials plus ***Proprietary*** features . See **TECHNICAL: *Heat Exchangers***.
F. Impractical measures to handle high-temperature helium. Expansion, contraction and metal stress issues.	Modern high-temperature gas turbine cooling methods and ***Proprietary*** features . See **TECHNICAL: *Reactor*** and ***He Turbine-Compressor.***

<u>Table Notes</u>: *(1) Summary issues* – **Ref. 42.**

CONCEPT

APPENDIX D: *Gas Reactors*

|Past Operational Issues

Table D3: Operational Issues

ISSUE[1]	**HYBRID Solution**
A. Core Vibrations. Typically produced by gas vortex shedding across slender shapes subsequently causing component fatigue damage.	Shapes designed to avoid or mitigate this phenomena.
B. Core Power Fluctuations. Typically caused by flow pressure differentials inducing movement of fuel blocks and/or core structures, subsequently limiting power output due to unstable neutron levels.	Pressure differential across core minimized by barrel bypass - see **TECHNICAL: *Reactor.*** Spring hold down devices (associated with removable decay heat circulator tube) also used at top of individual fuel/outlet plenum columns - see **TECHNICAL: *Reactor***. Core lateral restraints also used.
C. Water Ingress. Typically caused by steam generator tube leaks and ruptures subsequently causing material corrosion issues and component failures.	Steam generator not used with reactor. Low-pressure coolers unlikely to leak in any meaningful manner – see **TECHNICAL: *Reactor*.**
D. Dust.[2] Created by differential movement of core graphite materials. Problem compounded by fission product releases contaminating reactor systems.	Use of block type reactor and dust control measures - see **TECHNICAL** End-note item **M**.
E. Fission Product Release. Typically caused by excessive fuel temperatures and resulting in: contamination of reactor systems; and increase in radioactive source terms used with accident analyses and off-site releases.	Fuel temperatures well below limits - see **TECHNICAL**: ***Contrast/* Fuel.** Fuel pellets also employ additional protective coating – see **TECHNICAL: *Fuel*.**

/Past Operational Issues

Table D3 continued

ISSUE[1]	HYBRID Solution
F. *Oil Ingress thru Bearings*. Oil contaminates reactor system causing corrosion and carbon *dust* issues	Use of oil-free bearings – **see TECHNICAL: *He Turbine/Compressor.***
G. *Contamination of Helium Rotating Machinery*. Radioactive fission product laced dust associated with "tramp" uranium (occurs naturally in graphite) and Silver Ag110m (fission product can diffuse through SiC shell of fuel particles). Complicates machine maintenance and overhaul.	Helium turbine and compressor designed to be separately removed from ends of outer vessel as essentially complete units with minimal disassembly. Replacement units re-installed and old units decontaminated and overhauled. Similar to approach used with aeroderivatve gas turbines. Minimal radiation exposure by maintenance personnel Also see *Dust*, item D.
I. Shutdown Pellets Sticking. Caused by accidental massive water ingress and corrosion build-up on pellets. Would have prevented reactor shutdown.	Massive water ingress not possible. Pellet protective coating also employed.
J. Relief Valve Leakage. All relief valves tend to experience seat leakage if the valves are cycled more than a few times. If leakage excessive, valve seats and disks must be re-machined or replaced.	Dual relief valve and control valve configuration used to minimize cycling of primary ASME safety valve. Also avoids excessive system blowdown that could cause elevated fuel temperatures. See **TECHNICAL:** Chapter endnotes item **M**.

<u>Table Notes</u>: ***(1)*** *Summary issues – see* **Ref. 42.** None of these issues impact the public's safety. **(2)** Severe problem for pebble bed reactors, rendering them essentially unsuitable for operation with gas turbines and compressors - see **Ref. 43 & 52**

CONCEPT

APPENDIX D: *Gas Reactors*

/Operational Design Events

Table D4: Design Events

ISSUE	HYBRID Mitigation Measures
A. Small-helium-leak. Typically failure of small piping or tubing attached to reactor system.	Reactor automatically runs back (He turbine exhaust high temperature) and trips on helium low-low pressure and/or high-high exhaust temperature, with decay heat removed by plant systems – see **SAFETY: *Core Cooling***. *Public Unaffected*.
B. Reactor Block Rotating Machinery Over-speed. Caused by control malfunctions.	Machines all employ compressors and motor/generators that provide braking. On over-speed, plant controlled run-back with low-pressure helium turbine and main air compressor spinning down to proper speed. *Public Unaffected.*
C. Loss-of-Electrical Load. Caused by main generator trip.	Plant safely shuts-down. Reactor unaffected by loss of generator; bypass allows independent operation of helium rotating machinery & air compressor – see **TECHNICAL: *Thermal Cycle.*** Modern gas turbines typically accommodate load rejection without tripping. *Public Unaffected.*
D. Loss-of-Electrical AC Power. Caused by complete failure of off-site and onsite electrical generators.	Plant safely shuts-down. Highly unlikely due to diverse and robust electrical plant – see **TECHNICAL: *Electrical/Control***. In any case , fuel damage will not occur as core heat removed by DC power – see **SAFETY: *Reactor Heat Removal.*** *Public Unaffected.*
E. Dropped-Fuel-Bundles. Fuel handling accident potentially damages fuel, leading to fuel leakage.	3-point lift by articulated grapple employing positive mechanical lock - see **TECHNICAL: *Fuel***. Drop highly unlikely as is case with 1-point lift used with earlier block reactors. In any case, containment insures no radiation releases to environment. *Public Unaffected.*
F. Loss-of-air-compressor load.	Operational failure not possible; air compressor cannot be inadvertently stopped. *Public Unaffected.*

APPENDIX D: *Gas Reactors*

/Emergency Design Events

Table D5: Emergency Design Events

EVENT[1]	HYBRID Mitigation Measures
A. Major Loss-of-Helium. Caused by large hole in reactor system. Potential fuel overheating, damage & leakage issues.	**Public Unaffected.** Reactor's massive thermal capacity and multiple decay heat removal methods insure fuel temperatures well below limits. Fuel damage highly unlikely – see **SAFETY: *Core Cooling*.** Containment insures no radiation releases to environment.
B. Rapid-loss-of-flow. Caused by *He machinery-failures* or *major loss-of-helium* leading to potential fuel overheating and subsequent potential fuel damage/leakage issues.	**Public Unaffected.** Machinery coast-down most likely as helium turbine/compressor employs split-shaft design with separate motor/generators – see **TECHNICAL*: Helium Turbine-Compressor*.** Fuel damage will not occur as core heat removed – see **SAFETY: *Decay Heat***. Containment insures no environment radiation releases.
C. He-Rotating Machinery: Blade/ Stator Failures[2]. Compressor surge most likely initiating event[2] – also see *loss-of-helium*, *loss-of-flow*, and *loss-of-load*. Debris damages inner casings causing hole. Potential fuel damage issues.	**Public Unaffected.** Event unlikely as helium compressor designed to standards used with highly reliable commercial aircraft engines. In any case, debris can not reach reactor owing to machinery configuration – **see TECHNICAL: *Helium Turbine-Compressor.*** Also, double walled vessel and missile barriers protect reactor. Core heat removal (see **SAFETY: *Decay Heat Removal***) more than sufficient to protect fuel. Containment insures no environment radiation release.
E. Main-Compressor: Blade/Stator-Failures[2]. Caused by compressor surge.	**Public Unaffected.** Rotating helium machinery designed to ride-out event. Containment insures no environment radiation releases. Machine sits in bunkered compartment that stops blades/stators that may pierce casing from impacting reactor system.

CONCEPT

APPENDIX D: *Gas Reactors*

/Emergency Design Events

Table D5 Emergency Design Events *(continued)*

EVENT[1]	HYBRID Mitigation Measures
F. Major Failure of Reactor System Inner Vessels/Piping. Caused by catastrophic material failures. Potential fuel damage issues.	**Public Unaffected.** Inner components designed to Section VIII of ASME code with fatigue endurance also considered. Reactor pressure boundary remains intact and does not leak. Passive heat removal unaffected. Containment insures no undue radiation releases.
G. He-Rotating-Machinery: Shaft-Failures. Rotating shaft shears due to catastrophic material failures, leading to over-speed, stators & blade failures and subsequent pressure boundary failures , ultimately potentially leading to fuel damage – see *loss-of-helium, blade/stator-failure, loss-of-load*.	**Public Unaffected**. Shafts designed for highly reliable operation, with complete failure very unlikely – vibration monitoring systems provide advanced warning. Safety enhanced by (1) use of multiple shafts, and (2) braking action of compressors and motor/generators prevents run-away over-speed of helium machinery. Core heat removal (see **SAFETY: *Decay Heat Removal***) more than sufficient to protect fuel while containment insures public unaffected. Containment insures no undue radiation releases.
H. Main-Compressor: Shaft-Failure. *Causes same as above. Potential fuel overheating issues.*	**Public Unaffected**. Shafts designed for highly reliable operation, with complete failure very unlikely – vibration monitoring systems provide advanced warning. Core heat removal methods more than sufficient to protect fuel. Containment insures no undue radiation releases.
I. Station-Blackout. Caused by catastrophic and multiple failures in electrical systems. Fuel overheating, damage & leakage potential issues.	**Public Unaffected.** Highly unlikely event due to diverse and robust electrical plant - see **TECHNICAL: *Electrical/Control.*** Plant coasts down with core heat removal by passive systems – see **SAFETY: *Passive Heat Removal***, preventing fuel damage. Containment insures no undue radiation releases.

Table Notes: ***(1)*** *Additional discussions*– **Refs. 43 & 49. (2)** Based on gas turbine failure historical data.

CONCEPT

Table D6: Plausible Dangerous Events

EVENT	HYBRID Assessment
A. **<u>Combustion Turbine Explosion/Fire.</u>** Caused by major failures in fuel gas systems.	**Public Safe.** Combustion turbine fire detection, mitigation & suppression systems prevent/contain these events. In any case, the reactor is outside the blast zone with the outer shield building protecting the containment. Reactor plant unaffected.
B. **<u>Aircraft-Impact</u>**. Could result in *loss-of-heat sink* and/or *inability-to-shutdown-reactor*. Major fires likely.	**Public Safe.** Underground reactor protected by containment which, in turn, protected by shield building. Other barriers also employed –see **TECHNICAL; Elevation**. Owing to diversity of defense-in-depth, fires will not prevent reactor shutdown and core cooling. Fuel integrity maintained. Also, see assessments for cross-referenced events. Reactor plant unaffected.
C. **<u>Terrorist-Attack</u>**. Could result in *loss-of-heat sink* and/or *inability-to-shutdown-reactor.*	**Public Safe.** Bunkered "island" design with reactor and control room located underground with very limited access – see **TECHNICAL: *Plan View***. Concrete shield building protects containment with inner shield building also providing reactor protection. Loss of equipment located outside containment not necessary to protect public from undue radiation.

Table D7: Theorized Dangerous Events

EVENT[1]	HYBRID Assessment
A. **Inability-to-Shut-down-Reactor**. Fuel potentially severely damaged by excessive heat, ultimately resulting in undue public radiation exposure.	***Not Creditable***. Three independent shutdown methods used, one of which is completely diverse from the other two while two are Nuclear Safety Related – see **TECHNICAL: *Reactor***. Loss of power causes maneuvering & trip rods to drop into core by action of gravity while the third method (small pellets) is actively engaged (DC power) and relies on gravity. Each method protected by individual tubes that cannot be impaired or swept away by helium cross-flows. In any case, the nuclear physics of the core will always shutdown the reactor and the passive heat removal methods and containment insure *Public Not Affected.*
B. **Too-Rapid-Reactor-Cooldown.** Fuel potentially damaged by catastrophic thermal shock.	***Not Creditable***. Core's massive thermal inertia can not be overwhelmed by actual cooling mechanisms, all of which are gas based with modest heat removal capabilities. Never-the-less, passive heat removal methods plus reactor pressure boundary plus containment insure *Public Not Affected*.
C. **Complete-Severance-of-Interconnecting-Outer-Vessels/Pipes.** Caused by potential catastrophic materials failure.	***Not Creditable***. Outer vessels operate at low-pressures and are designed to Section III of ASME Code. Material distortion energies, endurance limits, and presence of inner piping do not support occurrence of guillotine double-ended failures. All items also subject to periodic inspection. Never-the-less, passive heat removal methods and containment insure *Public Not Affected.*
D. **Massive-Failure-of-Reactor System-Outer-Vessels.**[1] Caused by potential catastrophic materials failure.	***Not Creditable***. Outer vessel operate at low-pressures and are designed to Section III of ASME Code. Material distortion energies & endurance limits do not support occurrence of these events. All items subject to periodic inspection. Never-the-less, passive heat removal methods and containment insure *Public Not Affected.*

Table D7 continued

EVENT[1]	HYBRID Assessment
E. <u>Massive-Loss-of-All-Heat-Sinks.</u> Causes severe fuel overheating, ultimately resulting in undue public radiation exposure.	***<u>Not Creditable</u>***. Several diverse passive systems as well diverse and redundant active heat removal methods employed. See **SAFETY: *Core Cooling & Passive Heat Removal.***
F. <u>Massive-Air-Ingress</u>. Caused by helium escaping reactor system and being replaced by massive quantities of air that subsequently oxidizes, corrodes and damages fuel, ultimately resulting in undue public radiation exposure.	***<u>Not Creditable</u>***. Double walled reactor system design and arrangement precludes "chimney" effects if large hole present in outer vessels– see **TECHNICAL: *Reactor*** . Also, containment minimizes available oxygen, thereby preventing fuel damage.
G. <u>Massive-Water-Ingress.</u> Caused by water flooding reactor, creating fuel damage as well as explosive hydrogen gas generated by chemical reaction with graphite, ultimately resulting in undue public radiation exposure.	***<u>Not Creditable</u>***. Steam generators not employed. Location, arrangement and characteristics of low-pressure coolers cannot cause flooding of reactor – **TECHNICAL: *Reactor System***.
H. <u>Massive-Core-Disruption.</u> Catastrophic dislocation of core caused by severe pressure differentials stemming from massive failure of reactor vessel and/or reactor system. Leads to severe fuel damage.	***<u>Not Creditable</u>***. Double walled reactor system and conservative design of vessels preclude event. Core also mechanically prevented from uplift – see **TECHNICAL: *Reactor.*** Additionally, the core barrel and shroud vessel are mechanically prevented from lifting off their supports.

APPENDIX D: *Gas Reactors*

/Theorized Dangerous Events

Table D7 continued

EVENT[1]	HYBRID Assessment
I. Control-Rod-Ejection. Damages reactor vessel pressure boundaries causes loss of helium and leads to potential fuel damage issues, see major-*loss-of-helium.*	***Not Creditable***. Double walled reactor vessel arrangement prevents ejection of tubes containing flexible control rods & cables - see **TECHNICAL: *Control & Reactor.*** Control rods in core protected from massive pressure differentials; reside within separate tubes & holes in graphite blocks. In any case, reactor shuts down and core heat removal methods more than sufficient to protect fuel while containment insures no undue radiation releases.

Notes: *(1) Additional discussions –* **Refs. 43 & 49.**

CONCEPT

APPENDIX E: *NRC Safety Goals* /Advanced Reactors

Table E1: NRC safety Goals

NRC Goal[1]	HYBRID Assessment
A. Highly reliable and less complex shutdown and decay heat removal systems. The use of inherent or passive means to accomplish this objective is encouraged (negative temperature coefficient, natural circulation, etc.).	**Easily Met**. Multiple, highly reliable and simple (gravity) methods shutdown the reactor – *see* **TECHNICAL: *Reactor.*** Passive, diverse, simple reliable decay heat removal methods cool the reactor – see **SAFETY: *Decay Heat Removal.***
B. Longer time constants and sufficient instrumentation to allow for more diagnosis and management before reaching safety systems challenge and/or exposure of vital equipment to adverse conditions.	**Easily Met**. Active supplemental-safety systems minimize challenges to passive Nuclear Safety-Related systems – see **SAFETY: *Core Cooling.***
C. Simplified safety systems that, where possible, reduce required operator actions, equipment subjected to severe environmental conditions, and components needed for maintaining safe shutdown conditions. Such simplified systems should facilitate operator comprehension, reliable system function, and more straightforward engineering analysis.	**Easily Met**. The Nuclear-Safety-Related systems are inherently simple, readily understood and do not require operator or active actions to function – see **TECHNICAL** and **SAFETY**. These passive measures are not compromised by severe environmental conditions The measures insure safe reactor shutdown condition. Engineering analyses are straightforward owing to passive systems
D. Designs that minimize the potential for severe accidents and their consequences by providing sufficient inherent safety, reliability, redundancy, diversity, and independence in safety systems, with an emphasis on minimizing the potential for accidents over minimizing the consequences of such accidents.	**Easily Met**. Severe accidents are avoided – see **APPENDIX D: *Table D-7***. Rugged and simple design features minimize the potential for undue events while passive Safety-Related features assure the public is not affected by accidents & events. - see **APPENDIX D: *Table D-5***.

APPENDIX E: *NRC Safety Goals*
/Advanced Reactors

Table E1 -continued

NRC Goal[1]	HYBRID Assessment
E. Designs that provide reliable equipment in the balance of plant (BOP) (or safety-system independence from BOP) to reduce the number of challenges to safety systems.	**Easily Met**. The Nuclear-Safety-Related systems and Balance of Plant (Power Block) are completely independent of one-another – see **TECHNICAL** and **SAFETY** sections. Loss of BOP systems does not challenge Safety-Related systems –see **SAFETY:** ***Core Cooling***.
F. Designs that provide easily maintainable equipment and components.	**Easily Met**. However, issue is a plant reliability and personnel consideration only loosely related to NRC's fundamental purpose of protecting the public.
G. Designs that reduce potential radiation exposures to plant personnel.	**Easily Met**. However, this is a Plant Safety consideration only loosely related to the NRC's fundamental purpose of protecting the public. More aptly, should be an Occupational Health & Safety issue while being a lower tier personnel safety issue from plant perspective.
H. Designs that incorporate the defense-in-depth philosophy by maintaining multiple barriers against radiation release, and by reducing the potential for, and consequences of, severe accidents.	**Easily Met**. Multiple barriers used – see **SAFETY: Passive Barriers.** Potential and consequences of severe accidents approach zero for all intense purposes – See **SAFETY**.
I. Design features that can be proven by citation of existing technology, or that can be satisfactorily established by commitment to a suitable technology development program.	**Easily Met**. Hybrid based on collective experience of earlier gas reactors – see **Appendix D.** Hybrid based on practical experience versus cutting edge research.

APPENDIX E: *NRC Safety Goals* /Advanced Reactors

Table E1 -continued

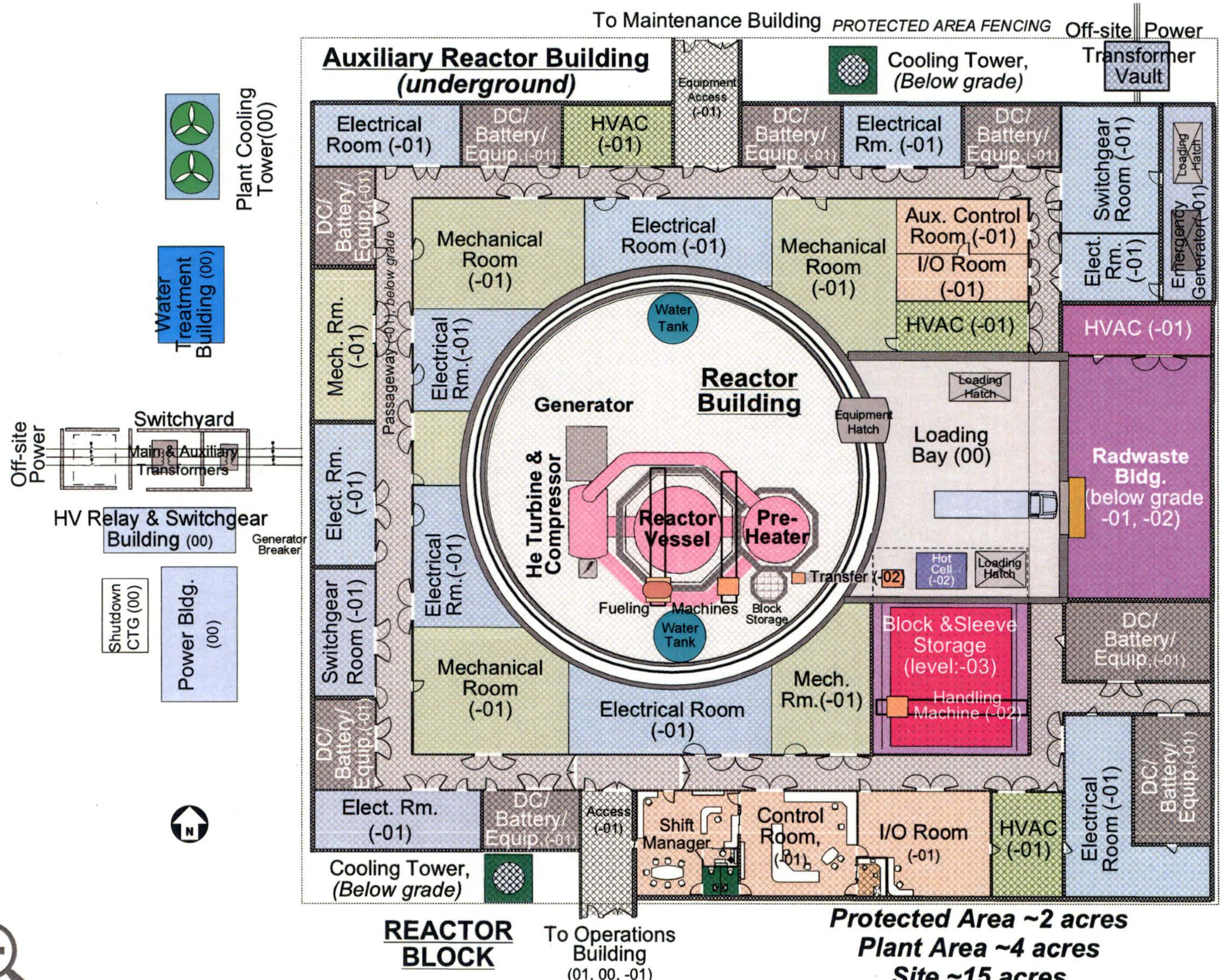
NRC Goal[1]	HYBRID Assessment
J. Designs that include considerations for safety and security requirements together in the design process such that security issues (e.g., newly identified threats of terrorist attacks) can be effectively resolved through facility design engineered security features, and formulation of mitigation measures, with reduced reliance on human actions.	**Easily Met**. Bunkered, largely underground "island' design with limited access renders threat remote – see **TECHNICAL:** ***Elevation*** & ***Plan View.***
K. Designs with features to prevent a simultaneous loss of containment integrity (including situations where the containment is by-passed), and the ability to maintain core cooling as a result of an aircraft impact, or identification of system designs that would provide inherent delay in radiological releases (if prevention of release is not possible).	**Easily Met**. Multiple barriers between reactor and outside environment insure core will not be damaged – see **SAFETY:** ***Passive Barriers***. Multiple and diverse core heat removal methods available if containment heat removal temporarily lost due to fire following aircraft impact – see **SAFETY**: ***Core Cooling.*** Radiological release will not occur. Further, plant fire suppression employ deluge systems (driven by diesel & electric pumps) to mitigate external fires.
L. Designs with features to prevent loss of spent fuel pool integrity as a result of an aircraft impact.	**Easily Met**. Spent fuel stored underground in casks in bunkered building - see **TECHNICAL:** ***Elevation.*** Pool of water is not used; natural convection air cooling.
M. Designs with features to eliminate or reduce the potential theft of nuclear materials.	**Easily Met**. Nuclear materials exceptionally difficult to access in reactor building and auxiliary reactor building – see **TECHNICAL:** ***Elevation***. Reactor block bunkered island design with very limited access – see **TECHNICAL:** ***Plan View***.

<u>Table Note</u>: *(1)* **Ref. 50**

CONCEPT

APPENDIX F: *Hybrid All-Nuclear*

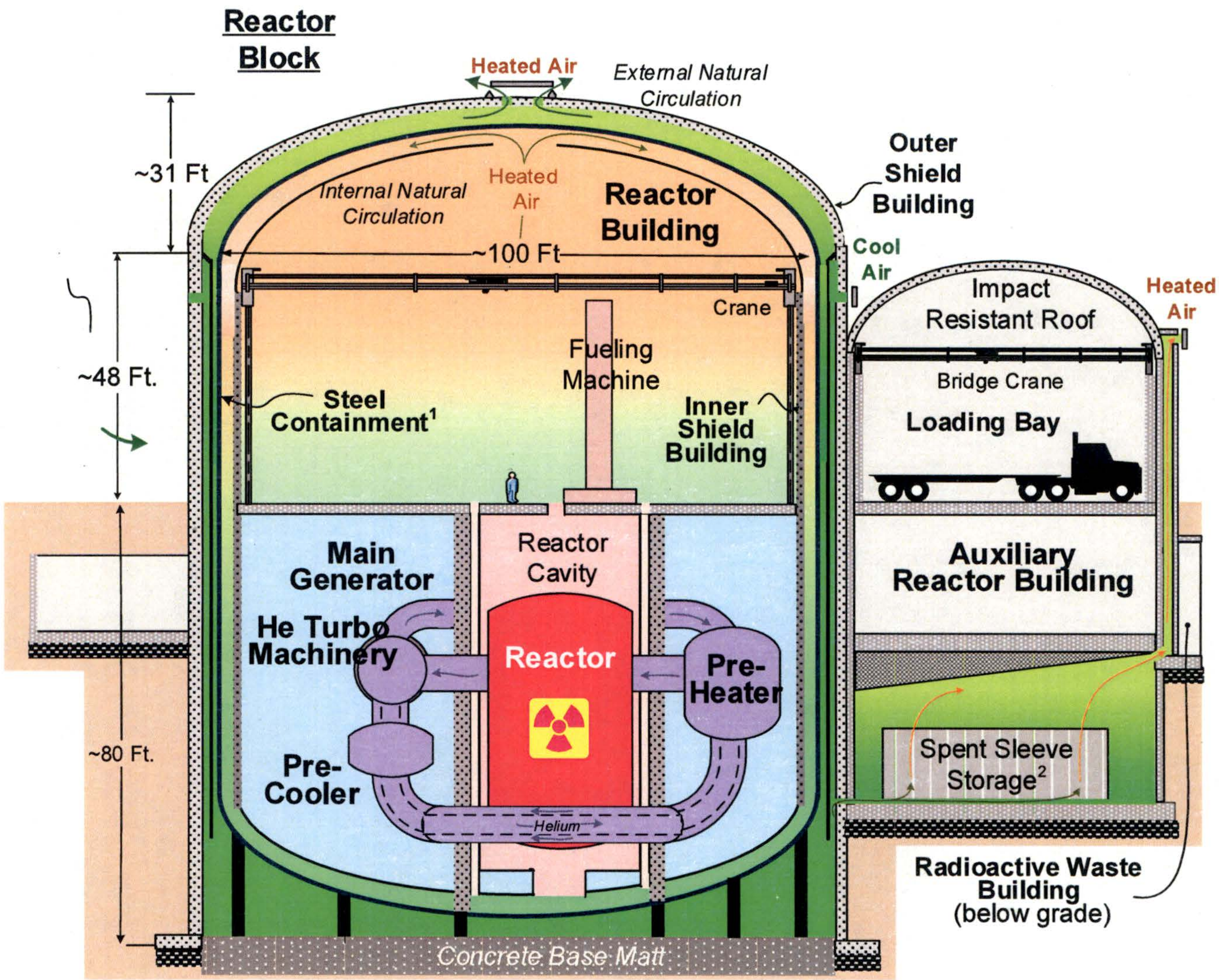
/Plan View



Protected Area ~2 acres
Plant Area ~4 acres
Site ~15 acres

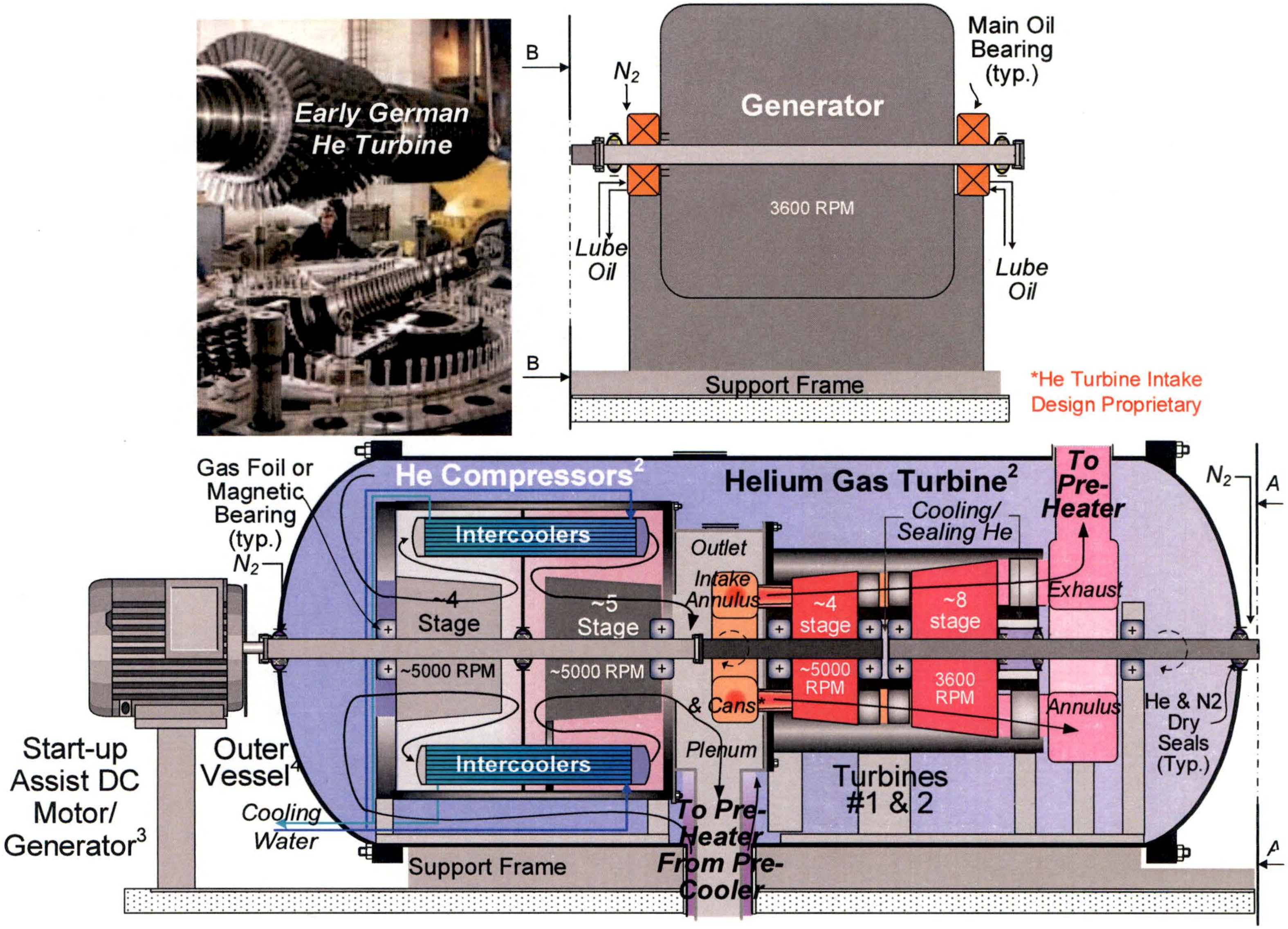
CONCEPT

APPENDIX F: *Hybrid All-Nuclear*
/Elevation



CONCEPT

APPENDIX F: *Hybrid All-Nuclear*
/Turbo-Generator



CONCEPT

APPENDIX F: *Hybrid All-Nuclear*
/Options

Table F1: Configurations

Hybrid Reactor Class	***Plant Electric MW(electric)***	***Reactor Output MW(thermal)***
A. Micro HYBRID/All-Nuclear		
(1) Type 2	*~4*	*~9 MW(t) reactor, 12 Fuel blocks, 6 columns, 2 rows*
(1) Type 3	*~13*	*~28 MW(t) reactor, 36 Fuel blocks, 12 columns, 3 rows*
(1) Type 4	*~26*	*~56 MW(t) reactor, 72 Fuel blocks, 18 columns, 4 rows*
(1) Type 5	*~44*	*~93 MW(t) reactor, 120 Fuel blocks, 24 columns, 5 rows*
A. Small HYBRID/All-Nuclear		
(1) Type 6	*~119*	*~250 MW(t) reactor, 324 Fuel blocks, 54 columns, 6 rows*
(1) Type 7	*~169*	*~357 MW(t) reactor, 462 Fuel Blocks, 66 Columns, 7 rows*
A. Baselines		
(1) Type 8	*~320*	*HYBRID-NUCLEAR/All-nuclear* *630 MW(t) Reactor, 816 Fuel Blocks, 102 columns, 8 rows*
(1) Type 8	*~950*	*HYBRID-NUCLEAR/Gas* *630. MW(t) Reactor, 816 Fuel Blocks, 102 columns, 8 rows*

Table Notes: *All configurations employ annular cores derived from simple scale down of baseline Hybrid.*

CONCEPT

APPENDIX F: *Hybrid All-Nuclear*
/Financial Contrast

Table F2: Economic Comparisons

PLANT TYPE	Net Output/Input, MW(e)/MW(t)	Overnight Cost[1] $/KW(e)	LCOE $/MWh
A. *HYBRID/All-Nuclear (Baseline)*	*320/630*	*$3000*	*$70*
B. *Micro HYBRID/All-Nuclear[3]*			
(1) Type 2	*~4/9*	*$5760*	*$320*
(1) Type 3	*~13/28*	*$5020*	*$160*
(1) Type 4	*~26/56*	*$4565*	*$130*
(1) Type 5	*~44/93*	*$4225*	*$100*
B. *Small HYBRID/All-Nuclear[3]*			
(1) Type 6	*~119/250*	*$3560*	*$80*
(1) Type 7	*~169/357*	*$3325*	*$75*
B. *For Comparative Purposes[4]*			
(1) Combined-Cycle Gas[5]	*925/--*	*$925*	*$50*
(1) Hybrid/Gas[5]	*950/630*	*$1100*	*$45*
(1) Large Nuclear	*~1115/3280*	*$5500*	*$100*
(1) Small Modular Reactor (12 units)[6]	*~662/2365*	*$6105*	*$125*
(1) Small Modular Reactor (1 unit)[6]	*~55/196*	*$9420*	*$200*

Table Notes: ***(1)*** *Engineer, Procure, Construct (EPC) costs.* ***(2)*** *All Level Cost of Energy (LCOE) calculated directly using Independent Power Producer economic model developed by Hybrid Power Technologies LLC. All plants operating at 90% capacity factor. No subsidies of any kind.* ***(3)*** *EPC cost developed using scaling factors typical of combined-cycle power plants whereby unit costs ($/KW) rise as station outputs become smaller –* ***see Ref. 1.*** ***(4)*** *Hybrid Power Technologies LLC calculated estimates.* ***(5)*** *Natural gas @ $5/MMBTU.* ***(6)*** *Using our scaling methodology, NUSCALE 12-unit station EPC factor ~1.1 relative to large conventional nuclear while single unit SMR EPC factor ~1.5 relative to 12-unit SMR.*

CONCEPT

APPENDIX G: *Hybrid* /Principal Design Criteria

Appendix A (General design Criteria) to Part 50 (Domestic Licensing of Production and Utilization Facilities) of Title 10 (Energy) the Code of Federal regulations, requires the use of Principal Design Criteria establish the necessary design, fabrication, construction, testing, and performance requirements that provide reasonable assurance that the facility can be operated without undue risk to the health and safety of the public.

Detailed below are the proposed **Principal Design Criteria for the Hybrid-Nuclear Power/Energy Plant** which is based on the General Design Criteria. Deletions from the original 10CFR Part 50 Appendix A are denoted by ~~Strikethroughs~~ while additions are-denoted by blue *Segoe Print.*

APPENDIX G: *Hybrid*
/Principal Design Criteria

CONCEPT

APPENDIX G: *Hybrid*
/Principal Design Criteria

CONCEPT

APPENDIX G: *Hybrid*
/Principal Design Criteria

Under the provisions of *Part* **§ 50.34**, of the *Code of Federal Regulations* an application for a construction permit must include the Principal Design Criteria for a proposed facility. Under the provisions of 10 CFR 52.47, 52.79, 52.137, and 52.157, an application for a design certification, combined license, design approval, or manufacturing license, respectively, must include the principal design criteria for a proposed facility. The Principal Design Criteria establish the necessary design, fabrication, construction, testing, and performance requirements for structures, *Nuclear-Safety* systems, and components important to safety; that is, structures, systems, and components that provide reasonable assurance that the facility can be operated without undue risk to the health and safety of the public.

These General Design Criteria establish minimum requirements for the principal design criteria for water-cooled nuclear power plants similar in design and location to plants for which construction permits have been issued by the Commission. The General Design Criteria are also considered to be generally applicable to other types of nuclear power units and are intended to provide guidance in establishing the principal design criteria for such other units. *The General Design Criteria, as modified herein, are the proposed Principal Design Criteria for the Hybrid-nuclear Advanced Gas-Cooled reactor energy production plant.*

CONCEPT

APPENDIX G: *Hybrid* /Principal Design Criteria

The development of the~~se~~ General Design Criteria is not yet complete. For example, some of the definitions need further amplification. Also, some of the specific design requirements for structures, systems, and components important to safety have not as yet been suitably defined. *Accordingly, the HYBRID Principal Design Criteria include: (1) definitions amplified to provide greater clarity and precision; and (2) more precise definition of some of the design requirements.* Their omission does not relieve any applicant from considering these matters in the design of a specific facility and satisfying the necessary safety requirements. These matters include:

(1) Consideration of the need to design against single failures of passive components in fluid systems *designated as Safety-Related* ~~important to safety~~. (See Definition of Single Failure.). *The HYBRID shall employ multiple passive Safety-Related fluid systems to protect against single failures.*

(2) Consideration of redundancy and diversity requirements for *Safety-Related* fluid systems ~~important to safety~~. A "system" could consist of a number of subsystems each of which is separately capable of performing the specified system ~~safety~~ *Safety-Related* function*(s)*. The minimum acceptable redundancy and diversity of subsystems and components within a subsystem, and the required interconnection and independence of the subsystems have not yet been developed or defined. (See Criteria 34, 35, 38, 41, and 44.) *The HYBRID shall employ passive, independent, and redundant Safety-Related passive fluid systems designed to remove reactor decay heat to provide redundancy and diversity.*

(3) Consideration of the type, size, and orientation of possible breaks in components of the reactor ~~coolant~~ pressure boundary in determining design requirements to suitably protect against postulated loss-of-coolant accidents. (See Definition of Loss of Coolant Accidents.). *The HYBRID shall employ pressure boundary configurations that suitably protect the fuel from loss-of-coolant induced fuel damage.*

(4) Consideration of the possibility of systematic, nonrandom, concurrent failures of redundant elements in the design of protection systems and reactivity control systems. (See Criteria 22, 24, 26, and 29.). *The HYBRID shall employ three diverse and redundant reactivity control systems.*

The Hybrid Principal Design Criteria have appropriately considered the above issues not necessarily suitably defined by the current General Design Criteria.

APPENDIX G: *Hybrid* /Principal Design Criteria

It is expected that the General Design Criteria will be augmented and changed from time to time as important new requirements for these and other features are developed.
~~There will be some water-cooled nuclear power plants for which the General Design Criteria are not sufficient and for which additional criteria must be identified and satisfied in the interest of public safety. In particular, it is expected that additional or different criteria will be needed to take into account unusual sites and environmental conditions, and for water-cooled nuclear power units of advanced design. Also, there may be water-cooled nuclear power units for which fulfillment of some of the General Design Criteria may not be necessary or appropriate. For plants such as these, departures from the General Design Criteria must be identified and justified.~~

Definitions and Explanations

1. Nuclear Power Unit. A nuclear power unit means a nuclear power reactor and associated equipment necessary for electric power generation and includes those structures, systems, and components required to provide reasonable assurance the facility can be operated without undue risk to the health and safety of the public. *The Hybrid nuclear unit consists of: (a) the Reactor Block containing the reactor (the core of which consists of support structures and graphite blocks containing: fuel, neutron reflectors, reactivity control features) and associated structures, systems and components as well as equipment that supports electrical generation; and (b) Power Block structures and equipment that provide for the generation and export of electrical energy into the grid and which may also include gas and steam turbines, including various support systems, components and structures.*

2 . Loss of coolant accidents. ~~Loss of coolant accidents~~ mean those postulated accidents that result from the loss of reactor coolant~~, at a rate in excess of the capability of the reactor coolant makeup system,~~ from breaks in the reactor coolant pressure boundary~~, up to and including a break equivalent in size to the double-ended rupture of the largest pipe of the reactor coolant system~~.[1]

{Summary justification: The Hybrid employs a passively cooled (post shutdown) gas reactor that uses graphite fuel with significantly lower core power densities than water reactors. Large losses of fluid do not cause loss of fuels integrity nor is a coolant makeup system required for the safety-related functions of mitigation of potential hazardous off-site doses caused by accidents.}

APPENDIX G: *Hybrid* /Principal Design Criteria

3. Single failure. A single failure means an occurrence which results in the loss of capability of a component to perform its intended *Safety-Related* ~~safety~~ function(s). Multiple failures resulting from a single occurrence are considered to be a single failure. *Safety-Related* fluid and *Safety-Related* electric systems are considered to be designed against an assumed single failure if neither (1) a single failure of any active component (assuming passive components function properly) nor (2) a single failure of a passive component (assuming active *Safety-Related* components function properly), results in a loss of the capability of the system to perform its *Safety-Related* functions.[2]

4. Anticipated operational occurrences. Anticipated operational occurrences mean those conditions of normal operation which are expected to occur one or more times during the life of the nuclear power unit and include but are not limited to loss of ~~power to~~ helium turbine/compressor ~~all recirculation pumps~~, tripping of the turbines and generator set**(s)**, ~~isolation of the main condenser~~, and loss of all offsite power.

5. Design Basis Event; A postulated incident used to establish the acceptable performance requirements of Safety-Related structures, systems, and components.

6. Specified Acceptable Fuel Design Limits: Maximum fuel pellet temperatures during normal, abnormal and emergency conditions.

7. Important-to-Safety. This term is not defined in the Code of Federal regulations and is therefore not used by the Hybrid Principal Design Criteria, having been replaced by more precise definitions – See Nuclear-Safety and Plant Safety definitions

8. Nuclear Safety. Refers to those system, structures and components specifically designed to protect the public from radiation and consists of Safety-Related and the sub-tiers definitions: "Important-to-Safety-Related", and "Nuclear-Waste", as defined below:

A. **Safety-Related:** (10CFR 50.2) :"Those Nuclear-Safety structures, systems and components that are relied upon to remain functional during and following Design Basis Events to insure:

(1)The integrity of the reactor ~~coolant~~ fission product boundary;

(2)The capability to shut-down the reactor and maintain it in a safe shutdown condition;

(3)The capability to prevent or mitigate the consequences of accidents which could result in potential offsite exposures comparable to the applicable guidelines set forth in 50.34 or 100.11"

APPENDIX G: *Hybrid* /Principal Design Criteria

B. **Important-to-Safety-Related**. Those Nuclear-Safety systems, structures, components, and measures provided to protect Safety-Related functions. Important-to-Safety-Related functions consist of: structures & barriers; limits (e.g. Technical Specifications associated with Safety-Related functions); fire protection; and security

C. **Nuclear-Waste:** Those Nuclear-Safety systems, structures, components, and measures provided to suitably protect the public from undue offsite releases from radioactive solids, fluids and gaseous wastes stored at the Nuclear Unit

9. <u>**Plant Safety**</u>. Refers to those system, structures, components and measures provided to protect plant equipment and personnel (as opposed to the general public) from hazards, as further defined below.

A. **Supplemental-Safety.** Those Plant-Safety systems, structures and components provided to actively protect the reactor core from damage.

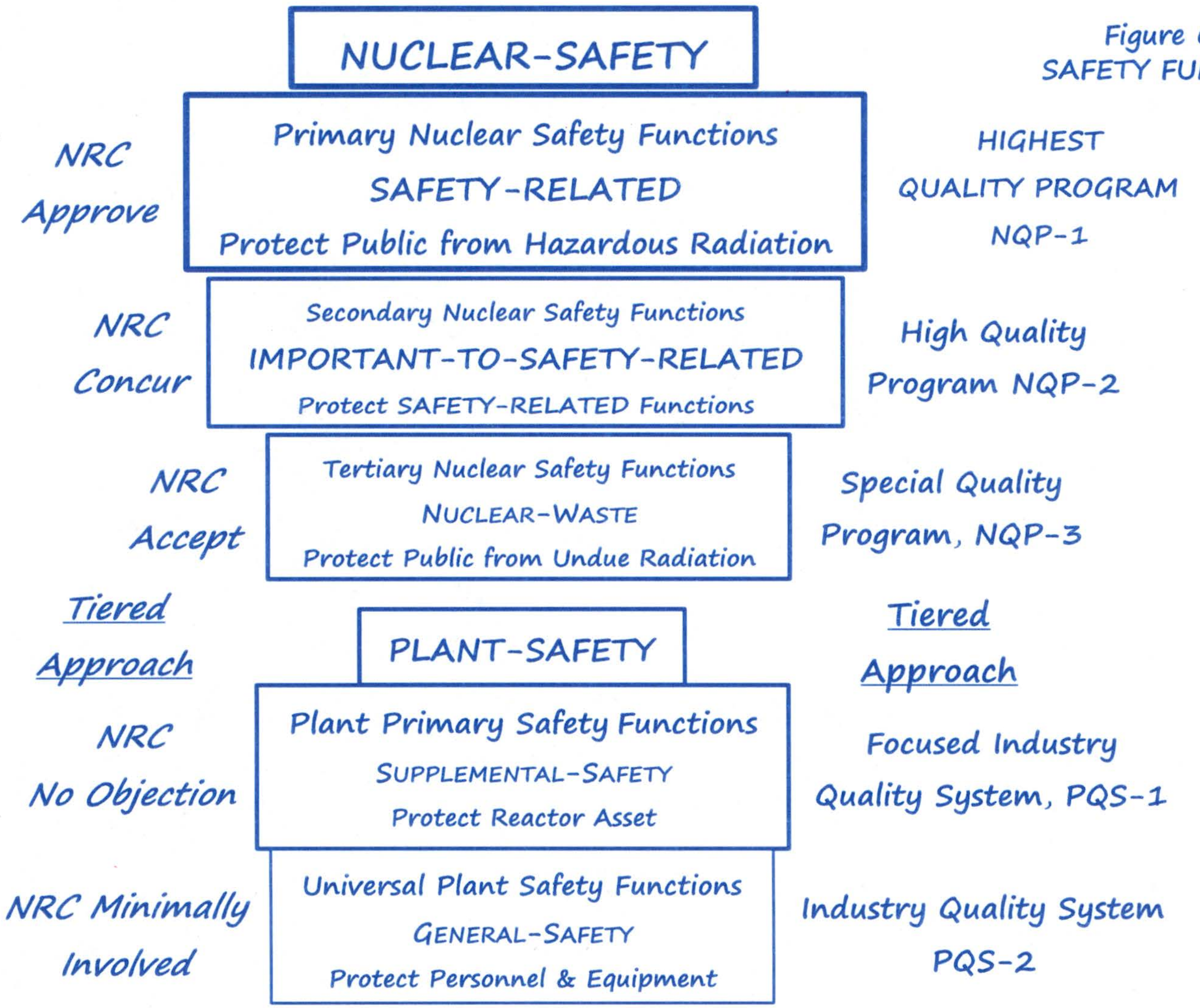
B. **General-Safety.** Those systems, structures, components, and measures provided to protect personnel and equipment.

Figure G-1 provides an illustrated explanation of Nuclear-Safety as used in herein. Terms involving NRC review efforts are defined below.

- <u>NRC Approve</u> means rigorous independent validation, as deemed appropriate by NRC, that applicant has convincingly demonstrated that the Safety-Related functions will be fulfilled.
- <u>NRC Concur</u> means reaching a sound conclusion that applicant has demonstrated that Important-to-Safety-Related protective functions will be fulfilled. This would include defined and bounded audits of select applicant activities, as considered appropriate by the NRC considering function's Nuclear-Safety significance.
- <u>NRC Accept</u> means reaching a reasonable conclusion that the applicant has demonstrated that the public is suitably protected from potential releases from radioactive waste stored at the nuclear facility.
- <u>NRC No Objection</u> means reaching an overview assessment that applicant's Supplemental-Plant-Safety functions can be reasonably accomplished.

APPENDIX G: *Hybrid*
/Principal Design Criteria

Figure G-1:
SAFETY FUNCTIONS



CONCEPT

APPENDIX G: *Hybrid* /Principal Design Criteria

CRITERIA

I. Overall Requirements

Criterion 1—***QUALITY STANDARDS AND RECORDS.*** Structures, systems, and components ~~important to safety~~ *performing Nuclear-Safety functions* shall be designed, fabricated, erected, and tested to quality standards commensurate with the importance of the *Nuclear-Safety* ~~safety~~ functions to be performed. Where generally recognized codes and standards are used, they shall be identified and evaluated to determine their applicability, adequacy, and sufficiency and shall be supplemented or modified as necessary to assure a quality product in keeping with the required *importance of the Nuclear-Safety* ~~safety~~ function. A *tiered* quality assurance program shall be established and implemented in order to provide adequate assurance that these *Nuclear-Safety* structures, systems, and components will satisfactorily perform their *Nuclear-Safety* ~~safety~~ functions *commensurate with the importance of the Nuclear-Safety functions*. Appropriate records, *commensurate with the importance of the Nuclear-Safety functions* of the design, fabrication, erection, and testing of structures, systems, and components important to safety shall be maintained by or under the control of the nuclear power unit licensee throughout the life of the unit.

Criterion 2—***DESIGN BASES FOR PROTECTION AGAINST NATURAL PHENOMENA.*** . *Commiserate with the importance of the Nuclear-Safety function, Nuclear-Safety* structures, systems, and components ~~important to safety~~ shall be designed to withstand the effects of natural phenomena such as earthquakes, tornadoes, hurricanes, floods, tsunami, and seiches without loss of capability to perform their *Nuclear-Safety* functions. The design bases for *Nuclear-Safety* structures, systems, and components shall reflect: (1) appropriate consideration of the most severe of the natural phenomena that have been historically reported for the site and surrounding area, with sufficient margin for the limited accuracy, quantity, and period of time in which the historical data have been accumulated, (2) appropriate combinations of the effects of normal and accident conditions with the effects of the natural phenomena and (3) the importance of the *Nuclear-Safety* functions to be performed.

{Summary justification: Not all Nuclear-Safety items are required to function for design basis protection against natural phenomena.}

CONCEPT

APPENDIX G: *Hybrid* /Principal Design Criteria

Criterion 3—**FIRE PROTECTION**. *Nuclear-Safety* structures, systems, and components~~ important to safety~~ shall be designed and located to minimize~~, consistent with other safety requirements~~, the probability and effect of fires and explosions. Noncombustible and heat resistant materials shall be used wherever practical throughout the *Nuclear-Safety portion of the* unit, particularly in locations such as the containment and control room. *Nuclear-Safety and Plant-Safety* fire detection and fighting systems of appropriate capacity and capability shall be provided and designed to minimize the adverse effects of fires on *Nuclear-Safety* structures, systems, and components ~~important to safety~~. Firefighting systems shall be designed to assure that their rupture or inadvertent operation does not significantly impair ~~the~~ *Nuclear-Safety* ~~safety capability of these~~ structures, systems, and components.

{Summary justification: Specific added regulatory fire protection restrictions on the entire power plant are excessive as the Power Block is designed to industry fire protection codes for power plants. Criteria 1 & 3 adequately protect the public in the context of Nuclear-Safety}

Criterion 4—**ENVIRONMENTAL AND DYNAMIC EFFECTS DESIGN BASES**. *Commiserate with the importance of the Nuclear-Safety function, Nuclear-Safety* structures, systems, and components ~~important to safety~~ shall be designed, , to accommodate the effects of and to be compatible with the environmental conditions associated with normal operation, maintenance, testing, and postulated accidents, including loss-of-coolant accidents. *Nuclear-Safety* ~~These~~ structures, systems, and components shall be appropriately protected against dynamic effects, including the effects of missiles, pipe whipping, and discharging fluids, that may result from equipment failures *including* ~~and~~ from events and conditions outside the *Nuclear-Safety portion of the unit* and nuclear power unit. However, dynamic effects associated with postulated pipe ruptures in *the Reactor Block* may be excluded from the design basis when analyses reviewed and approved by the Commission demonstrate that the probability *of hazardous radiological effects on the public from* fluid system piping rupture is extremely low under conditions consistent with the design basis for the piping.

{Summary justification: Not all Nuclear-Safety items are required to protect the public from hazardous radiation releases promulgated by Design Basis Events. Piping ruptures are highly unlikely to challenge the integrity of the Hybrid core because passive, diverse and redundant Safety-Related core heat removal systems are employed and the core power density is significantly less than that of water reactors}

CONCEPT

APPENDIX G: *Hybrid* /Principal Design Criteria

Criterion 5—***SHARING OF STRUCTURES, SYSTEMS, AND COMPONENTS***. *Safety-Related and Important-to-Safety-Related* structures, systems, and components ~~important to safety~~ shall not be shared among nuclear power units ~~unless it can be shown that such sharing will not significantly impair their ability to perform their safety functions, including, in the event of an accident in one unit, an orderly shutdown and cooldown of the remaining units.~~

*{Summary justification: Shared items is inconsistent with the Hybrid **Nuclear-Safety** philosophy of achieving an exceptionally high level of protection of the public from radiation hazards, including protection from cascading failures}*

II. Protection by Multiple Fission Product Barriers

Criterion 10—***REACTOR DESIGN.*** The *Nuclear-Safety* reactor core and associated *Plant-Safety* coolant, control, and *Nuclear-Safety* protection systems shall be designed with appropriate margin to assure that Specified Acceptable Fuel Design Limits are not exceeded during any condition of normal operation, including the effects of anticipated operational occurrences.

Criterion 11—***REACTOR INHERENT PROTECTION.*** The *Nuclear-Safety* reactor core and associated *Plant-Safety* coolant systems shall be designed so that in the power operating range the net effect of the prompt inherent nuclear feedback characteristics tends to compensate for a rapid increase in reactivity.

Criterion 12—***SUPPRESSION OF REACTOR POWER OSCILLATIONS.*** The *Nuclear-Safety* reactor core and associated *Plant-Safety* coolant, control, and *Nuclear-Safety* protection systems shall be designed to assure that power oscillations which can result in conditions exceeding Specified Acceptable Fuel Design Limits are not possible or can be reliably and readily detected and suppressed.

Criterion 13—***INSTRUMENTATION AND CONTROL***. *Plant-Safety* instrumentation shall be provided to monitor variables and systems over their anticipated operational ranges for normal operation, *including* for anticipated operational occurrences. *Nuclear-Safety instrumentation shall be provided for normal, abnormal and accident conditions* ~~as appropriate~~ to assure ~~adequate~~ *Safety-Related functions are properly performed and monitored,* ~~safety~~, including those variables and systems that can affect the fission process, the integrity of the reactor core, the reactor-coolant ~~pressure~~ boundary, and the containment and its associated systems. Appropriate *configuration management* controls shall be provided to maintain these *Nuclear-Safety and applicable Plant-Safety* variables and systems within prescribed operating ranges.

CONCEPT

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Criterion 14—***REACTOR COOLANT ~~PRESSURE~~ BOUNDARY*.** The *Safety-Related* reactor coolant ~~pressure~~ boundary shall be designed, fabricated, erected, and tested so as to have ~~an extremely~~ *a very* low probability of abnormal leakage, of rapidly propagating failure, and of gross rupture.

{Summary justification: Extremely low boundary failure probabilities are unnecessary. Unlike conventional water reactors, piping ruptures and leakage are highly unlikely to challenge the fission product retaining integrity of the Hybrid core because (1) diverse, passive Safety-Related core decay heat removal systems are employed and (2) the core's power density is a small fraction of that of water reactor cores. Further, the fuel is not prone to melting, unlike that of conventional water reactors.}

Criterion 15—***REACTOR COOLANT SYSTEM DESIGN***. The *Safety-Related* reactor coolant system and associated *Plant-Safety* systems ~~auxiliary~~, *Plant-Safety* control system, and *Safety-Related reactor* protection systems shall be designed with sufficient margin to assure that the design conditions of the reactor coolant ~~pressure~~ boundary are not exceeded during any condition of normal operation, including anticipated operational occurrences.

Criterion 16—***CONTAINMENT DESIGN*.** The *Safety-Related* reactor containment and associated *Nuclear-Safety and Plant-Safety* systems shall be provided to establish an essentially leak-tight barrier against the uncontrolled release of radioactivity to the environment and to assure that the *Nuclear-Safety* containment design conditions ~~important to safety~~ are not exceeded for as long as postulated accident conditions require.

CONCEPT

APPENDIX G: *Hybrid* /Principal Design Criteria

Criterion 17—**ELECTRIC POWER SYSTEMS**. *Safety-Related low-voltage electrical power, control, and distribution systems, including batteries, shall be provided to support Nuclear-Safety-Related functions.* An onsite *Plant-Safety* electric power *supply* system *(e.g. a dedicated diesel/ generator and/or gas turbine/generator)* and an offsite electric power *supply* system shall be provided to permit *normal and abnormal* functioning of *Nuclear-Safety* structures, systems, and components ~~important to safety~~. ~~The safety function for each system (assuming the other system is not functioning) shall be to provide sufficient capacity and capability to assure that (1) specified acceptable fuel design limits and design conditions of the reactor coolant pressure boundary are not exceeded as a result of anticipated operational occurrences and (2) the core is cooled and containment integrity and other vital functions are maintained in the event of postulated accidents.~~

The onsite *Safety-Related* ~~electric power supplies, including the batteries, and the onsite~~ electric distribution *and Safety-Related Reactor Protection systems* shall have sufficient independence, redundancy, and testability to perform their *Safety-Related* functions assuming a single failure.

The *Plant-Safety* electric power from the transmission network to the onsite *Plant-Safety medium and high-voltage* electric distribution system shall be supplied by two physically independent circuits (not necessarily on separate rights of way) designed and located so as to minimize to the extent practical the likelihood of their simultaneous failure under operating and postulated accident and environmental conditions. A switchyard common to both circuits is *not* acceptable. ~~Each of these circuits shall be designed to be available in sufficient time following a loss of all onsite alternating current power supplies and the other offsite electric power circuit, to assure that specified acceptable fuel design limits and design conditions of the reactor coolant pressure boundary are not exceeded. One of these circuits shall be designed to be available within a few seconds following a loss-of-coolant accident to assure that core cooling, containment integrity, and other vital safety functions are maintained.~~

~~Provisions shall be included to minimize the probability of losing electric power from any of the remaining supplies as a result of, or coincident with, the loss of power generated by the nuclear power unit, the loss of power from the transmission network, or the loss of power from the onsite electric power supplies.~~

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{Summary justification: The Hybrid employs diverse and redundant Safety-Related passive systems to remove reactor core decay heat while the core power density is significantly smaller than that of water reactors. A passively cooled Safety-Related containment system is also employed. The fuel melting issues associated with water reactors are not present, thus mitigating the need for the highly prescriptive Electric Power System requirements of the General Design Criteria. The Hybrid electrical system is highly reliable, although the impetus for this dependability is driven primarily by Plant-Safety considerations.}

Criterion 18—***INSPECTION AND TESTING OF ELECTRIC POWER SYSTEMS***. *Safety-Related electrical* ~~power~~ systems ~~important to safety~~ shall be designed to permit appropriate periodic inspection and testing of important areas and features, such as wiring, insulation, connections, and switchboards, to assess the continuity of the systems and the condition of their components. The *Safety-Related* systems shall be designed with a capability to test periodically, *and in particular*: (1) the operability and functional performance of the components of the *Safety-Related* systems, such as onsite power sources *(batteries),* relays, switches, and buses, and (2) the operability of the *Safety-Related* systems as a whole and, under conditions as close to design as practical, the full operation sequence that brings the systems into operation, including operation of applicable portions of the protection system, and the transfer of power among the nuclear power unit, the offsite power system, and the onsite power system.

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/Principal Design Criteria

Criterion 19—**CONTROL ROOM.** A control room shall be provided from which actions can be taken to operate the nuclear power unit *in a nuclear safe manner* ~~safely~~ under normal conditions and to maintain *Nuclear-Safety functions* ~~it in~~ a ~~nuclear safe condition~~ under accident conditions, including *Design Basis Events* ~~loss of coolant accidents~~. Adequate radiation protection shall be provided to permit *as needed* access and occupancy of the control room under accident conditions without personnel receiving radiation exposures shall not exceed 0.05 Sv (5 rem) total effective dose equivalent (TEDE) as defined in § 50.2 for the duration of the accident. ~~in excess of 5 rem whole body, or its equivalent to any part of the body, for the duration of the accident.~~

Safety-Related equipment at appropriate locations outside the control room shall be provided (1) with a design capability for prompt hot shutdown of the reactor, including necessary *Safety-Related* instrumentation ~~and controls~~ to *confirm the unit is in a safe condition and* if necessary maintain, *using Plant-Safety equipment,* the unit in a safe condition during hot shutdown, and (2) with a potential capability for subsequent cold shutdown of the reactor through the use of suitable procedures.

~~Applicants for and holders of construction permits and operating licenses under this part who apply on or after January 10, 1997, applicants for design approvals or certifications under part 52 of this chapter who apply on or after January 10, 1997, applicants for and holders of combined licenses or manufacturing licenses under part 52 of this chapter who do not reference a standard design approval or certification, or holders of operating licenses using an alternative source term under § 50.67, shall meet the requirements of this criterion, except that with regard to control room access and occupancy, adequate radiation protection shall be provided to ensure that radiation exposures shall not exceed 0.05 Sv (5 rem) total effective dose equivalent (TEDE) as defined in § 50.2 for the duration of the accident.~~

{Summary justification: The Hybrid employs passive diverse and redundant Safety-Related systems to remove reactor core decay heat and passive Safety-Related pressure boundaries (fuel coatings, reactor coolant pressure boundary and containment pressure boundary) to protect the public from hazardous radiation. These systems do not require or rely on plant operator actions to meet their Safety-Related functions. The Plant operator's principal duty is to assure that the asset is properly functioning as an energy production facility}

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III. Protection and Reactivity Control Systems

Criterion 20—***PROTECTION SYSTEM FUNCTIONS***. The *Plant-Safety control system* shall be designed (1) to initiate automatically the operation of appropriate systems including the reactivity control systems, to assure that specified acceptable fuel design limits are not exceeded as a result of anticipated operational occurrences. ~~and (2) the~~ *The Safety-Related reactor protection system shall be designed* to sense accident conditions and to initiate the operation of *Safety-Related reactivity control* systems and *components to assure that Specified Acceptable Fuel Design Limits are not exceeded* ~~important to safety~~.

Criterion 21—***PROTECTION SYSTEM RELIABILITY AND TESTABILITY***. The ~~protection~~ *Safety-Related reactor protection* system shall be designed for high functional reliability and in-service testability commensurate with the safety *-related* functions to be performed. Redundancy and independence designed into the protection system shall be sufficient to assure that (1) no single failure results in loss of the protection function and (2) removal from service of any component or channel does not result in loss of the required minimum redundancy unless the acceptable reliability of operation of the protection system can be otherwise demonstrated. The protection system shall be designed to permit periodic testing of its functioning when the reactor is in operation, including a capability to test channels independently to determine failures and losses of redundancy that may have occurred.

Criterion 22—***PROTECTION SYSTEM INDEPENDENCE***. The ~~protection~~ *Safety-Related reactor protection* system shall be designed to assure that the effects of natural phenomena, and of normal operating, maintenance, testing, and postulated accident conditions on redundant channels do not result in loss of the protection function, or shall be demonstrated to be acceptable on some other defined basis. Design techniques, such as functional diversity or diversity in component design and principles of operation, shall be used to the extent practical to prevent loss of the protection function.

Criterion 23—***PROTECTION SYSTEM FAILURE MODES***. The ~~protection~~ *Safety-Related reactor protection* system *and Plant-Safety reactivity control system* shall be designed to fail into a safe state or into a state demonstrated to be acceptable on some other defined basis if conditions such as disconnection of the system, loss of energy (e.g., electric power, instrument air), or postulated adverse environments (e.g., extreme heat or cold, fire, pressure, steam, water, and radiation) are experienced.

CONCEPT

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Criterion 24—***Separation of Protection and Control Systems***. The *Safety-Related reactor* protection system shall be separated from *Plant-Safety* control systems ~~to the extent that failure of any single control system component or channel, or failure or removal from service of any single protection system component or channel which is common to the control and protection systems leaves intact a system satisfying all reliability, redundancy, and independence requirements of the protection system. Interconnection of the protection and control systems shall be limited so as to assure that safety is not significantly impaired.~~

Criterion 25—***Protection System Requirements for Reactivity Control Malfunctions***. The *Safety-Related reactor* protection *(including Safety-Related reactivity control system)* system *and the Plant-Safety reactivity control system* shall be designed to assure that Specified Acceptable Fuel Design Limits are not exceeded for any single malfunction of the reactivity control systems, such as accidental withdrawal (not ejection or dropout) of control rods.

Criterion 26—***Reactivity Control System Redundancy and Capability.*** Two independent *Safety-Related* reactivity control systems of different design principles shall be provided. *These Safety-Related systems shall assure that Specified Acceptable Fuel Design Limits are not exceeded under limiting Design Basis Events.*

A Plant-Safety reactivity control system ~~One of the systems~~ shall use control rods~~, preferably including a positive means for inserting the rods,~~ and shall be capable of reliably controlling reactivity changes to assure that under conditions of normal operation, including anticipated operational occurrences, and with appropriate margin for malfunctions such as stuck rods, Specified Acceptable Fuel Design Limits are not exceeded *and* ~~The second reactivity control system~~ shall be capable of reliably controlling the rate of reactivity changes resulting from planned, normal power changes (including xenon burnout) to assure acceptable fuel design limits are not exceeded.

One of the *three reactivity control* systems shall be capable of holding the reactor core subcritical under cold conditions.

Criterion 27—***Combined Reactivity Control Systems Capability.*** The *Safety-Related and Plant-Safety* reactivity control systems shall be designed to have a combined capability~~, in conjunction with poison addition by the emergency core cooling system,~~ of reliably controlling reactivity changes to assure that under postulated *limiting Design Basis Event* accident conditions and with appropriate margin for stuck rods the capability to cool the core is maintained.

CONCEPT

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Criterion 28—**REACTIVITY LIMITS.** The *Safety-Related and Plant-Safety* reactivity control systems shall be designed with appropriate limits on the potential amount and rate of reactivity increase to assure that the effects of postulated reactivity accidents can neither (1) result in damage to the reactor ~~coolant~~ pressure boundary greater than limited local yielding nor (2) sufficiently disturb the core, its support structures or other reactor pressure vessel internals to impair significantly the capability to cool the core. These postulated reactivity accidents shall include consideration of rod ejection (unless prevented by positive means), rod dropout, ~~steam line rupture~~, changes in reactor coolant temperature and pressure, and cold ~~water~~ coolant addition.

{Summary justification: Steam generators are not employed with the reactor coolant system nor are water injection systems}

Criterion 29—**PROTECTION AGAINST ANTICIPATED OPERATIONAL OCCURRENCES.** The *Plant-Safety and Nuclear-Safety* protection and reactivity control systems shall be designed to assure an extremely high probability of accomplishing their *Plant-Safety and Nuclear-Safety* ~~safety~~ functions in the event of anticipated operational occurrences.

IV. Fluid Systems

Criterion 30—**QUALITY OF REACTOR COOLANT ~~PRESSURE~~ BOUNDARY.** Components which are part of the *Safety-Related* reactor coolant ~~pressure~~ boundary shall be designed, fabricated, erected, and tested to ~~the highest~~ *very high* quality standards ~~practical~~. *Nuclear-Waste* means shall be provided for detecting and, to the extent practical, identifying the location of the source of reactor coolant leakage.

{Summary justification: Unlike actively cooled pressurized water reactors, the Hybrid's gas reactor: (a) relies on passive and diverse Safety-related core decay removal; and (b) loss-of-coolant accidents do not lead to potentially catastrophic fuel melting and subsequent hazardous off-site radiation doses to the public. As such, the "very highest" quality levels are unnecessary.}

Criterion 31—**FRACTURE PREVENTION OF REACTOR ~~COOLANT~~ PRESSURE BOUNDARY.** The *Safety-related* reactor coolant ~~pressure~~ boundary shall be designed with sufficient margin to assure that when stressed under operating, maintenance, testing, and postulated accident conditions (1) the boundary behaves in a non-brittle manner and (2) the probability of rapidly propagating fracture is minimized. The design shall reflect consideration of service temperatures and other conditions of the boundary material under operating, maintenance, testing, and postulated accident conditions and the uncertainties in determining (1) material properties, (2) the effects of irradiation on material properties, (3) residual, steady state and transient stresses, and (4) size of flaws.

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Criterion 32—***INSPECTION OF REACTOR COOLANT ~~PRESSURE~~ BOUNDARY.*** Components which are part of the *Safety-Related* reactor coolant ~~pressure~~ boundary shall be designed to permit (1) periodic inspection and testing of important areas and features to assess their structural and leak-tight integrity, and (2) an appropriate material surveillance program for the reactor pressure vessel.

Criterion 33—***REACTOR COOLANT MAKEUP.*** A *Supplemental-Safety* system to supply reactor coolant makeup for protection against small breaks in the reactor coolant ~~pressure~~ boundary shall be provided. The system *Supplemental-Safety* function shall be to assure that Specified Acceptable Fuel Design Limits are not exceeded as a result of reactor coolant loss due to leakage from the reactor coolant ~~pressure~~ boundary and rupture of small piping or other small components which are part of the boundary. The system shall be designed to assure that for onsite electric power system operation (assuming offsite power is not available) and for offsite electric power system operation (assuming onsite power is not available) the system *Supplemental-Safety* function can be accomplished using the piping, pumps, and valves used to maintain coolant inventory during normal reactor operation.

Criterion 34—***RESIDUAL HEAT REMOVAL.*** A *Supplemental-Safety* system to remove residual heat shall be provided. The Supplemental-Safety ~~system~~ function shall be to transfer fission product decay heat and other residual heat from the reactor core at a rate such that Specified Acceptable Fuel Design Limits and the design conditions of the reactor coolant ~~pressure~~ boundary are not exceeded.

Suitable redundancy in components and features, and suitable interconnections, leak detection, and isolation capabilities shall be provided to assure that for onsite electric power system operation (assuming offsite power is not available) and for offsite electric power system operation (assuming on-site power is not available) the system *Supplemental-Safety* function can be accomplished, assuming a single failure.

CONCEPT

APPENDIX G: *Hybrid*
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Criterion 35—**EMERGENCY CORE COOLING.** ~~A~~ *Passive Safety-Related* systems to provide abundant emergency core cooling shall be provided. The system *Safety-Related* ~~safety~~ function shall be to transfer heat from the reactor core following any *Design Basis Event* ~~loss of reactor coolant at a rate~~ *to assure Specified Acceptable Fuel Design Limits are not exceeded.* ~~(1) fuel and clad damage that could interfere with continued effective core cooling is prevented and (2) clad metal-water reaction is limited to negligible amounts~~.

Suitable redundancy in components and features, and suitable interconnections, leak detection, isolation, and containment capabilities shall be provided to assure that for onsite electric power system operation (assuming offsite power is not available) and for offsite electric power system operation (assuming onsite power is not available) the system safety function can be accomplished, assuming a single failure.

{Summary justification: The fuel does not employ cladding and metal water reactions are not possible. Also, neither water injection nor are steam generators employed.

Criterion 36—**INSPECTION OF EMERGENCY CORE COOLING SYSTEM.** The *passive, Safety-Related* emergency core cooling systems shall be designed to permit appropriate periodic inspection of important components, ~~such as spray rings in the reactor pressure vessel, water injection nozzles, and piping,~~ to assure the integrity and capability of the system.

Criterion 37—**TESTING OF EMERGENCY CORE COOLING SYSTEM.** The *passive, Safety-Related* emergency core cooling systems shall be designed to permit appropriate periodic ~~pressure and~~ functional testing to assure (1) the structural and leak-tight integrity of its components, (2) the operability and performance of the ~~active~~ components of the system, and (3) the operability of the system as a whole and, under conditions as close to design as practical, the performance of the full operational sequence that brings the system into operation, including operation of applicable portions of the *Safety-Related reactor* protection system, the transfer between normal and emergency power sources, and the operation of *any* associated *passive* cooling water system.

CONCEPT

Criterion 38—***CONTAINMENT HEAT REMOVAL.*** A *passive Safety-Related* system to remove heat from the reactor containment shall be provided. The system *Safety-Related* ~~safety~~ function shall be to reduce ~~rapidly~~, consistent with the functioning of other associated systems, the containment pressure and temperature following any *Design Basis Event including* loss-of-coolant accident and maintain them at acceptably low levels.

Suitable redundancy in components and features, and suitable interconnections, leak detection, isolation, and containment capabilities shall be provided to assure that for onsite electric power system operation (assuming offsite power is not available) and for offsite electric power system operation (assuming onsite power is not available) the system safety function can be accomplished, assuming a *active* single failure.

Criterion 39—***INSPECTION OF CONTAINMENT HEAT REMOVAL SYSTEM.*** The *passive Safety-Related* containment heat removal system shall be designed to permit appropriate periodic inspection of important components~~, such as the torus, sumps, spray nozzles, and piping~~ to assure the integrity and capability of the system.

Criterion 40—***TESTING OF CONTAINMENT HEAT REMOVAL SYSTEM.*** The *passive Safety-Related* containment heat removal system shall be designed to permit appropriate periodic ~~pressure and~~ functional testing to assure (1) the structural and leak-tight *(if applicable)* integrity of its components, (2) the operability and performance of the ~~active~~ components of the system, and (3) the operability of the system as a whole, and under conditions as close to the design as practical the performance of the full operational sequence that brings the system into operation, including operation of applicable portions of the *Safety-Related Reactor* protection system, the transfer between normal and emergency power sources, and the operation of ~~the~~ associated *Supplemental-Safety* cooling water system.

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Criterion 41—***CONTAINMENT ATMOSPHERE CLEANUP*****.** Systems to control fission products, hydrogen, oxygen, and other substances which may be released into the reactor containment *shall not be credited for mitigating radiological releases associated with limiting Design Basis Events nor shall they be credited to maintain the integrity of the Safety-Related containment system.* ~~be provided as necessary to reduce, consistent with the functioning of other associated systems, the concentration and quality of fission products released to the environment following postulated accidents, and to control the concentration of hydrogen or oxygen and other substances in the containment atmosphere following postulated accidents to assure that containment integrity is maintained.~~

~~Each system shall have suitable redundancy in components and features, and suitable interconnections, leak detection, isolation, and containment capabilities to assure that for onsite electric power system operation (assuming offsite power is not available) and for offsite electric power system operation (assuming onsite power is not available) its safety function can be accomplished, assuming a single failure.~~

Criterion 42—***INSPECTION OF CONTAINMENT ATMOSPHERE CLEANUP SYSTEMS***. *If used,* containment atmosphere cleanup systems shall be designed to permit appropriate periodic inspection of important components, such as filter frames, ducts, and piping to assure the integrity and capability of the systems.

Criterion 43—***TESTING OF CONTAINMENT ATMOSPHERE CLEANUP SYSTEMS***. *If used,* containment atmosphere cleanup systems shall be designed to permit appropriate periodic pressure and functional testing to assure (1) the structural and leak tight integrity of its components, (2) the operability and performance of the active components of the systems such as fans, filters, dampers, pumps, and valves and (3) the operability of the systems as a whole and, under conditions as close to design as practical, the performance of the full operational sequence that brings the systems into operation, including operation of applicable portions of the protection system, the transfer between normal and emergency power sources, and the operation of associated systems.

CONCEPT

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Criterion 44—**COOLING ~~WATER~~ SYSTEMS** ~~A~~ *Diverse Supplemental-Safety* systems to transfer heat from *Reactor Block Nuclear-Safety* structures, systems, and components ~~important to safety,~~ to an ultimate heat sink shall be provided. The systems ~~safety~~ *Supplemental-Safety* function shall be to transfer the combined heat load of these structures, systems, and components under normal operating and accident conditions.

Suitable redundancy in components and features, and suitable interconnections, leak detection, and isolation capabilities shall be provided to assure that for onsite *Supplemental-Safety* electric power system operation (assuming offsite power is not available) and for offsite electric power system operation (assuming onsite power is not available) the systems safety function can be accomplished, assuming a single failure.

{Summary justification: Both active air and water fluid systems are employed for heat removal in support of Supplemental-Safety functions.}

Criterion 45—***INSPECTION OF COOLING ~~WATER~~ SYSTEMS***. ~~The~~ *Supplemental-Safety* cooling ~~water~~ systems shall be designed to permit appropriate periodic inspection of important components, such as heat exchangers and piping, to assure the integrity and capability of the systems.

Criterion 46—***TESTING OF COOLING ~~WATER~~ SYSTEMS***. The *Supplemental-Safety* cooling ~~water~~ systems shall be designed to permit appropriate periodic pressure and functional testing to assure (1) the structural and leak tight integrity of its components, (2) the operability and the performance of the active components of the system, and (3) the operability of the system as a whole and, under conditions as close to design as practical, the performance of the full operational sequence that brings the system into operation for reactor shutdown and for loss-of-coolant accidents, including operation of applicable portions of the *Plant Safety* protection system and the transfer between normal and emergency power sources.

CONCEPT

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V. Reactor Containment

Criterion 50—***CONTAINMENT DESIGN BASIS.*** The *Safety-Related* reactor containment structure, including access openings, penetrations, and the *passive Safety-Related* containment heat removal system shall be designed so that the containment structure and its internal compartments can accommodate, without exceeding the design leakage rate and with sufficient margin, the calculated pressure and temperature conditions resulting from any loss-of-coolant accident. This margin shall reflect consideration of (1) the effects of potential energy sources which have not been included in the determination of the peak conditions~~, such as energy in steam generators and as required by § 50.44 energy from metal-water and other~~ chemical reactions that may result from degradation but not total failure of *passive Safety-Related* emergency core cooling functioning, (2) the limited experience and experimental data available for defining accident phenomena and containment responses, and (3) the conservatism of the *calculation* model and input parameters.

Criterion 51—***FRACTURE PREVENTION OF CONTAINMENT PRESSURE BOUNDARY.*** The *Safety-Related* reactor containment boundary shall be designed with sufficient margin to assure that under operating, maintenance, testing, and postulated accident conditions (1) its ferritic materials behave in a non-brittle manner and (2) the probability of rapidly propagating fracture is minimized. The design shall reflect consideration of service temperatures and other conditions of the containment boundary material during operation, maintenance, testing, and postulated accident conditions, and the uncertainties in determining (1) material properties, (2) residual, steady state, and transient stresses, and (3) size of flaws.

Criterion 52—***CAPABILITY FOR CONTAINMENT LEAKAGE RATE TESTING.*** The *Safety-Related* reactor containment and other equipment which may be subjected to containment test conditions shall be designed so that periodic integrated leakage rate testing can be conducted at containment design pressure.

Criterion 53—***PROVISIONS FOR CONTAINMENT TESTING AND INSPECTION.*** The *Safety-Related* reactor containment shall be designed to permit (1) appropriate periodic inspection of all important areas, such as penetrations, (2) an appropriate surveillance program, and (3) periodic testing at containment design pressure of the leak tightness of penetrations which have resilient seals and expansion bellows.

CONCEPT

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Criterion 54—***PIPING SYSTEMS PENETRATING CONTAINMENT***. Piping systems penetrating primary *Safety-Related* reactor containment shall be provided with leak detection, isolation, and containment capabilities having redundancy, reliability, and performance capabilities which reflect the importance to ~~safety~~ *Nuclear-Safety* of isolating these piping systems. Such piping systems shall be designed with a capability to test periodically the operability of the isolation valves and associated apparatus and to determine if valve leakage is within acceptable limits.

Criterion 55—***REACTOR COOLANT ~~PRESSURE~~ BOUNDARY PENETRATING CONTAINMENT.*** Each line that is part of the *Safety-Related* reactor coolant ~~pressure~~ boundary and that penetrates primary reactor containment shall be provided with containment isolation valves as follows, unless it can be demonstrated that the containment isolation provisions for a specific class of lines, such as instrument lines, are acceptable on some other defined basis:

(1) One locked closed isolation valve inside and one locked closed isolation valve outside containment; or

(2) One automatic isolation valve inside and one locked closed isolation valve outside containment; or

(3) One locked closed isolation valve inside and one automatic isolation valve outside containment. A simple check valve may not be used as the automatic isolation valve outside containment; or

(4) One automatic isolation valve inside and one automatic isolation valve outside containment. A simple check valve may not be used as the automatic isolation valve outside containment.

Isolation valves outside containment shall be located as close to containment as practical and upon loss of actuating power, automatic isolation valves shall be designed to take the position that provides greater safety.

Other appropriate requirements to minimize the probability or consequences of an accidental rupture of these lines or of lines connected to them shall be provided as necessary to assure adequate safety. Determination of the appropriateness of these requirements, such as higher quality in design, fabrication, and testing, additional provisions for in-service inspection, protection against more severe natural phenomena, and additional isolation valves and containment, shall include consideration of the population density, use characteristics, and physical characteristics of the site environs.

Criterion 56—***PRIMARY CONTAINMENT ISOLATION*.** Each line that connects directly to the containment atmosphere and penetrates primary reactor containment shall be provided with containment isolation valves as follows, unless it can be demonstrated that the containment isolation provisions for a specific class of lines, such as instrument lines, are acceptable on some other defined basis:

(1) One locked closed isolation valve inside and one locked closed isolation valve outside containment; or

(2) One automatic isolation valve inside and one locked closed isolation valve outside containment; or

(3) One locked closed isolation valve inside and one automatic isolation valve outside containment. A simple check valve may not be used as the automatic isolation valve outside containment; or

(4) One automatic isolation valve inside and one automatic isolation valve outside containment. A simple check valve may not be used as the automatic isolation valve outside containment.

Isolation valves outside containment shall be located as close to the containment as practical and upon loss of actuating power, automatic isolation valves shall be designed to take the position that provides greater safety.

Criterion 57—***CLOSED SYSTEM ISOLATION VALVES*.** Each line that penetrates primary reactor containment and is neither part of the reactor coolant ~~pressure~~ boundary nor connected directly to the containment atmosphere shall have at least one containment isolation valve which shall be either automatic, or locked closed, or capable of remote manual operation. This valve shall be outside containment and located as close to the containment as practical. A simple check valve may not be used as the automatic isolation valve.

VI. Fuel and Radioactivity Control

Criterion 60—***CONTROL OF RELEASES OF RADIOACTIVE MATERIALS TO THE ENVIRONMENT*.** The nuclear power unit design shall include Nuclear-Safety (Nuclear Waste) means to control suitably the release of radioactive materials in gaseous and liquid effluents and to handle radioactive solid wastes produced during normal reactor operation, including anticipated operational occurrences. Sufficient holdup capacity shall be provided for retention of gaseous and liquid effluents containing radioactive materials, particularly where unfavorable site environmental conditions can be expected to impose unusual operational limitations upon the release of such effluents to the environment.

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Criterion 61—***FUEL STORAGE AND HANDLING AND RADIOACTIVITY CONTROL***. The *Nuclear-Safety (Nuclear Waste)* fuel storage and handling, radioactive waste, and other systems which may contain radioactivity shall be designed to assure adequate *Nuclear-Safety* under normal and postulated accident conditions. These systems shall be designed (1) with a capability to permit appropriate periodic inspection and testing of *Nuclear-Waste* components ~~important to safety~~, (2) with suitable shielding for *Plant-Safety* radiation protection, (3) with appropriate *Nuclear-Waste* containment, confinement, and filtering systems, (4) with a *passive Nuclear-Safety* residual heat removal capability having reliability and testability that reflects the *Nuclear-Safety* ~~importance to safety~~ of decay heat and other residual heat removal, and (5) to prevent significant reduction in fuel storage ~~coolant~~ heat removal *capability* ~~inventory~~ under *Design Basis Events* and accident conditions.

Criterion 62—***PREVENTION OF CRITICALITY IN FUEL STORAGE AND HANDLING***. Criticality in the fuel storage and handling system shall be prevented by physical *Nuclear-Waste* systems or processes, preferably by use of geometrically safe configurations.

Criterion 63—***MONITORING FUEL AND WASTE STORAGE***. Appropriate *Nuclear-Waste* systems shall be provided in fuel storage and radioactive waste systems and associated handling areas (1) to detect conditions that may result in loss of residual heat removal capability and excessive radiation levels and (2) to initiate appropriate *Plant and Nuclear* safety actions.

Criterion 64—***MONITORING RADIOACTIVITY RELEASES***. *Nuclear Waste* ~~M~~means shall be provided for monitoring the reactor containment atmosphere, spaces containing components for recirculation of loss-of-coolant accident fluids, effluent discharge paths, and the plant environs for radioactivity that may be released from normal operations, including anticipated operational occurrences, and from postulated accidents.

End-Notes

[1]Further details relating to the type, size, and orientation of postulated breaks in specific components of the reactor coolant pressure boundary are under development.

[2]Single failures of passive components in electric systems should be assumed in designing against a single failure. The conditions under which a single failure of a passive component in a fluid system should be considered in designing the system against a single failure are under development.