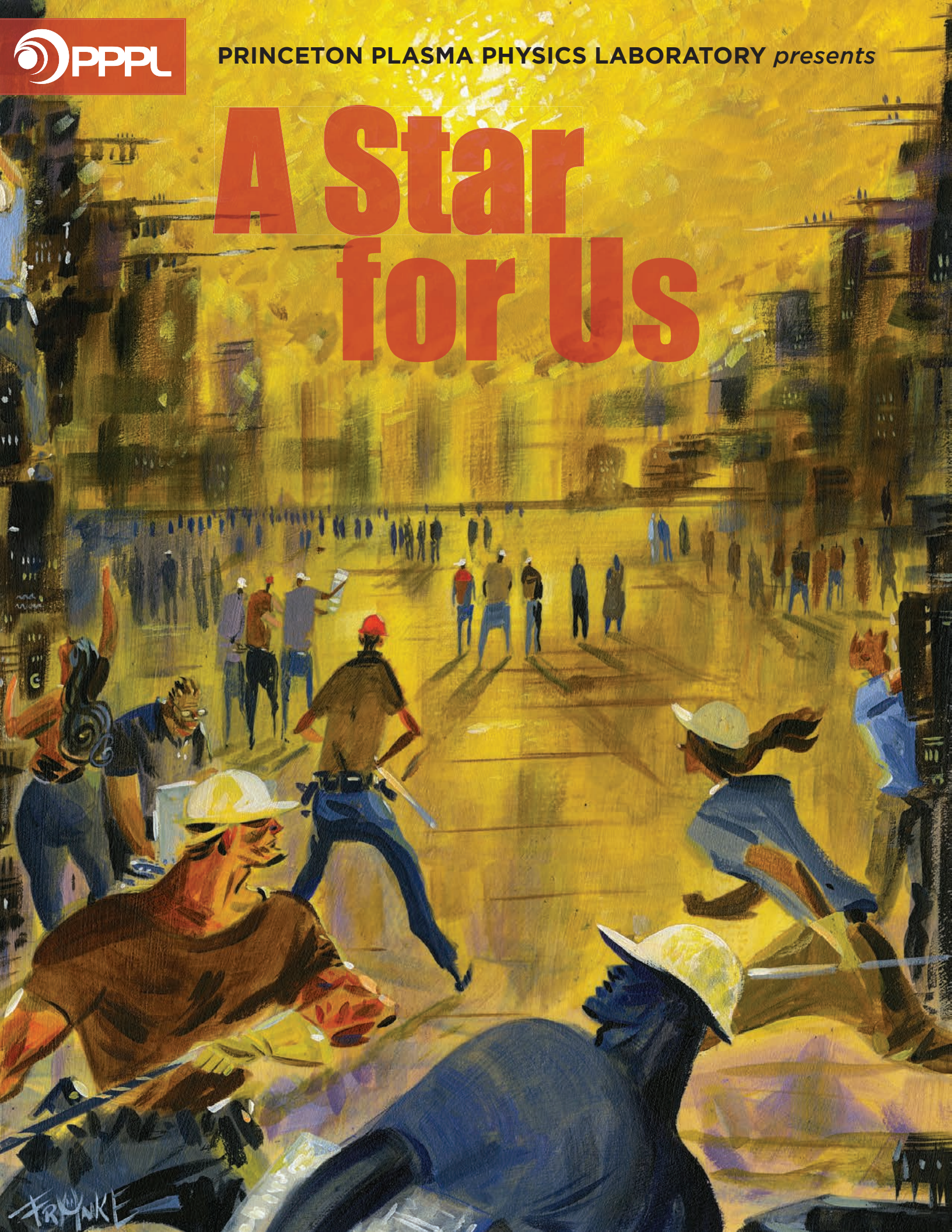
PPPL

PRINCETON PLASMA PHYSICS LABORATORY *presents*

A Star for Us



The Princeton Plasma Physics Laboratory (PPPL) is a collaborative national center for plasma and fusion energy sciences managed by Princeton University for the U.S. Department of Energy (DOE). It is the only DOE Laboratory devoted to these areas and it is committed to being the leading U.S. institution investigating the science of magnetic fusion energy.

Today, the National Spherical Torus Experiment-Upgrade (NSTX-U), the Laboratory's flagship endeavor, is set to advance the worldwide quest for fusion as a safe, clean and virtually limitless source of energy for producing electricity. The original NSTX began operating in 1999 and our 21st century upgrade is poised to bring the world closer to the dawn of a bold new Energy Age.

This illustrated science booklet tells the story of the promise of fusion energy and the ambitious steps that are being taken to achieve it.


PRINCETON PLASMA PHYSICS LABORATORY PRESENTS
A Star for Us
NINETY-THREE MILLION MILES FROM A SUN IGNITED BY THE UNIVERSAL POWER OF FUSION, THE WORLD OF HUMANS ORBITS AND SPINS IN SILENCE. DRIVEN BY MORTAL DREAMS.
FROM CAVES TO SKYSCRAPERS, THE SUN'S POWER DEFINED OUR PAST AND SHAPES OUR PRESENT. ITS HEAT GIVES US HOPE. ITS LIGHT GIVES US REASON.
AND NOW, THE TIME HAS COME FOR US TO MASTER THAT WHICH MADE US AND OUR WORLD, AND BUILD A FUTURE UNLIKE ANY OUR ANCESTORS IMAGINED.
Writer: Sajan Saini
Artist: Frank Espinosa

1 : The Fusion Barrier

IMAGINE A NEW WORLD WHERE OUR URBAN AMBITIONS YIELD NEW NATURAL ECOSYSTEMS.

HUMANITY'S ACCELERATING HUNGER FOR **LIGHTING, TRANSPORTATION,** AND **COMMUNICATION,** INTEGRATED INTO A RENEWABLE REALITY.

A WORLD FREE FROM THE FEARS OF AN ATMOSPHERIC CARBON BUDGET. WHERE OUR CHILDREN TAKE UP AN INTIMATE BOND WITH LAND AND SEA...

PROFITING FROM A BOUNTY OF ELECTRICITY AS **LIMITLESS** AS THE OCEANS.

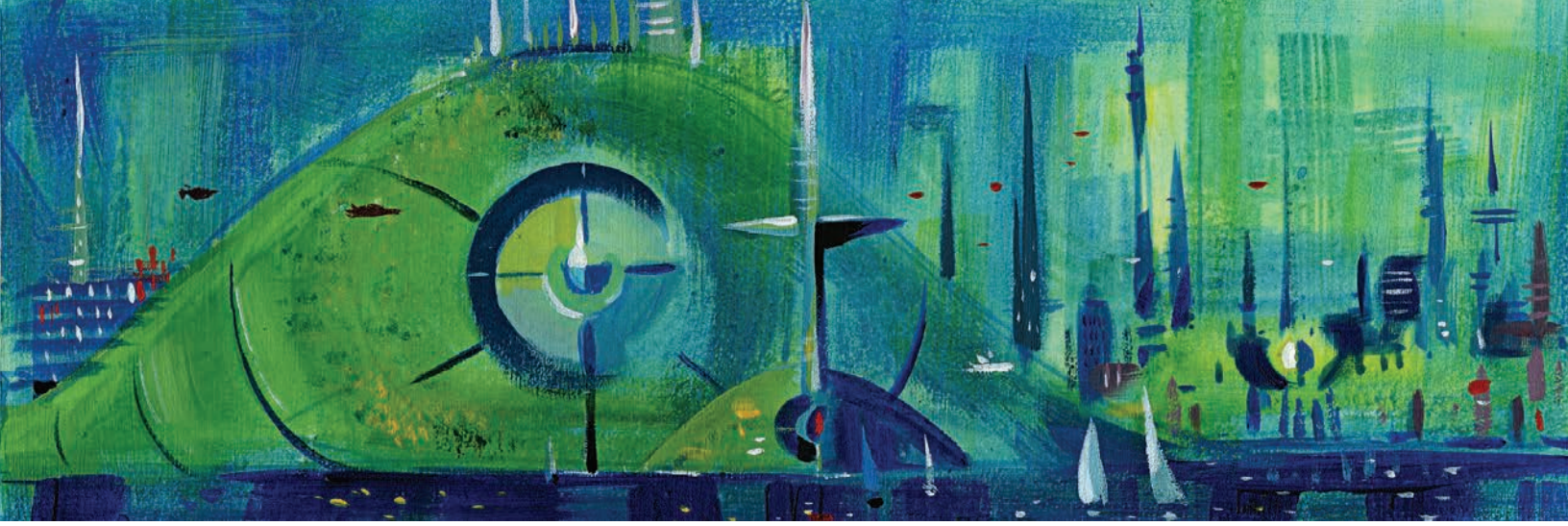
IT WILL BE A WORLD **POWERED** BY A COLLABORATION OF **SMARTER, CLEANER** TECHNOLOGIES.

WHERE OUR ABILITIES TO SEE, MOVE, AND SPEAK ARE AMPLIFIED BY A POWER MORE **SAFE, PLENTIFUL, RELIABLE--**

AND **COMMONPLACE,** THAN THE ENERGY INDUSTRIES OF TODAY.

FUSION TECHNOLOGY, IN PARTICULAR, WILL DELIVER THESE PROMISES. FOR IT IS THE POWER OF A **STAR** THAT CREATED AND SUSTAINS OUR WORLD.

WHAT MORE WILL WE CREATE WHEN WE TAKE UP THIS POWER IN OUR INDUSTRIOUS **HAND?**



BEFORE WE IMAGINE THE FUTURE, WE MUST LEARN FROM THE **PAST.**

THE QUEST FOR MANMADE FUSION EMERGED FROM THE ARMS RACE OF THE COLD WAR, AS SUPERPOWER NATIONS STRIVED TO UNLEASH THE POWER LOCKED WITHIN ATOMIC NUCLEI.

BELOW THE CRITICAL DENSITY OF A CHAIN-REACTION, FUSION IS **BENIGN**-- A NUCLEAR PROCESS CONSUMING NATURALLY **ABUNDANT** HYDROGEN, TO GENERATE **HARMLESS** HELIUM.

AT THE ATOMS FOR PEACE CONFERENCE IN 1958, SCIENTISTS SHARED THEIR FINDINGS: FUSION WOULD BE ATTAINED NOT BY COMPETITION, BUT BY **COLLABORATION.**

AT PRINCETON UNIVERSITY, LYMAN SPITZER HAD ALREADY TAKEN UP THE CHALLENGE.

THE SUN AND THE STARS **FUSED** ATOMIC NUCLEI UNDER THE CRUSH OF GRAVITY, WHICH COULDN'T BE RECREATED ON EARTH.

BUT WITH A MAGNETIC FIELD, A **FACSIMILE** STAR COULD BE WROUGHT ON EARTH. IT WOULD NOT BE EASY, IT WOULD TAKE MUCH TIME AND GREAT EFFORT.

IT COULD BE DONE, IN **THEORY.**

2: Building a Star

WITHIN THE SUN RUMBLES A FIERY, GASEOUS **PLASMA**-- ATOMS HEATED TO 10 MILLION DEGREES CELSIUS, THEIR ELECTRONS BREAKING FREE TO EXPOSE **CHARGED** NUCLEI.

CREATING A PLASMA ISN'T A **TECHNICAL** CHALLENGE. WE CREATE PLASMAS **RELIABLY** INSIDE NEON LIGHTS, SELECT FLATSCREEN TVS, AND PLASMA GLOBES.

BUT THAT ISN'T **SUFFICIENT** TO ACHIEVE FUSION... FOR THE ELECTRIC REPULSION OF CHARGED NUCLEI DRIVES THEM APART.

IF THE SUN'S GRAVITY CAN FORCE NUCLEI INTO A PROXIMITY A MILLION MILLION TIMES SMALLER THAN A CENTIMETER-- A **TITANIC** SHORT-RANGE NUCLEAR FORCE TAKES **HOLD** AND LIBERATES **VAST ENERGIES** LOCKED INSIDE NUCLEAR MASSES.

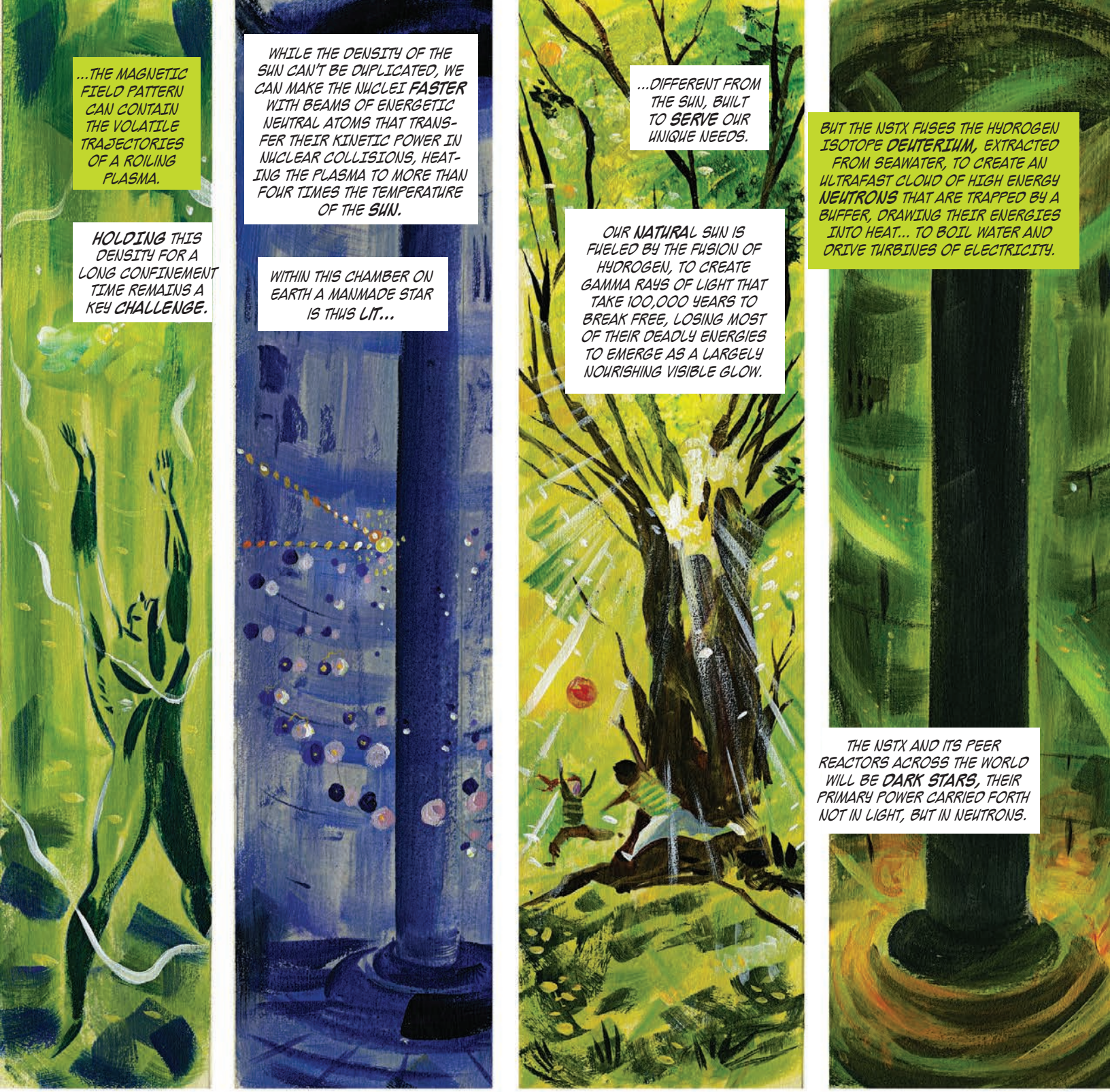
ON **EARTH,** WE HAVE NO MEANS TO OVERCOME THIS REPULSION WITH GRAVITY.

YET WE CAN FIND OTHER MEANS TO CONFINE, BRINGING LIKE NUCLEI **CLOSE ENOUGH, LONG ENOUGH...**

AND MAKE THEM **FAST** ENOUGH TO OVERCOME REPULSION, AND **FUSE.**

WITH A MAGNETIC FIELD, CHARGED HYDROGEN ISOTOPES ARE CLOSELY HELD INSIDE THE NATIONAL SPHERICAL TORUS EXPERIMENT **(NSTX)** AT A DENSITY THAT **RAISES** THE RATE OF FUSION--

PROVIDED THAT...


...THE MAGNETIC FIELD PATTERN CAN CONTAIN THE VOLATILE TRAJECTORIES OF A ROILING PLASMA.
HOLDING THIS DENSITY FOR A LONG CONFINEMENT TIME REMAINS A KEY CHALLENGE.
WHILE THE DENSITY OF THE SUN CAN'T BE DUPLICATED, WE CAN MAKE THE NUCLEI FASTER WITH BEAMS OF ENERGETIC NEUTRAL ATOMS THAT TRANSFER THEIR KINETIC POWER IN NUCLEAR COLLISIONS, HEATING THE PLASMA TO MORE THAN FOUR TIMES THE TEMPERATURE OF THE SUN.
WITHIN THIS CHAMBER ON EARTH A MANMADE STAR IS THUS LIT...
...DIFFERENT FROM THE SUN, BUILT TO SERVE OUR UNIQUE NEEDS.
OUR NATURAL SUN IS FUELED BY THE FUSION OF HYDROGEN, TO CREATE GAMMA RAYS OF LIGHT THAT TAKE 100,000 YEARS TO BREAK FREE, LOSING MOST OF THEIR DEADLY ENERGIES TO EMERGE AS A LARGELY NOURISHING VISIBLE GLOW.
BUT THE NSTX FUSES THE HYDROGEN ISOTOPE DEUTERIUM, EXTRACTED FROM SEAWATER, TO CREATE AN ULTRAFAST CLOUD OF HIGH ENERGY NEUTRONS THAT ARE TRAPPED BY A BUFFER, DRAWING THEIR ENERGIES INTO HEAT... TO BOIL WATER AND DRIVE TURBINES OF ELECTRICITY.
THE NSTX AND ITS PEER REACTORS ACROSS THE WORLD WILL BE DARK STARS, THEIR PRIMARY POWER CARRIED FORTH NOT IN LIGHT, BUT IN NEUTRONS.


THE SUN, DESPITE ITS COSMIC SCALE, REMAINS INEFFICIENT AT FUSION, WHILE OUR EARTHBORN STAR WILL CREATE A POWER DENSITY 100,000 TIMES GREATER.
WHEN FUNCTIONAL, IT WILL BE MANKIND'S GREATEST ENGINEERING FEAT: HEATING SEAWATER TO CREATE A GRAND SURPLUS OF ELECTRICITY... FROM A PLASMA THE SIZE OF A HOUSE.

3: Holding it Better

A KEY ENGINEERING CHALLENGE FOR STABLE FUSION IS INCREASED **CONFINEMENT TIME.**

AT **PPPL**, THE SPHERICAL TORUS DESIGN OF THE NSTX CHAMBER WAS A CRITICAL STEP TOWARDS HOLDING ONTO A STABLE PLASMA... AND NOW IT'S TIME TO **UPGRADE.**

FIFTEEN YEARS OF EXPERIMENT AND THEORY REVEAL HOW TO REDUCE THE RATIO OF **OUTWARD** PLASMA PRESSURE VERSUS INWARD MAGNETIC PRESSURE, DOUBLING OUR ABILITY TO CONFINE THE UNRULY GAS WITH A **LARGER** CENTER STACK **MAGNET.**

BUT THIS YIELDS **NEW** COMPLICATIONS.

WITH THE LARGER MAGNETIC FIELD, **TREMENDOUS** FORCES WILL RUN UNCHECKED ALONG THE CENTER STACK, RENDING IT AND THE **NSTX-U** TO PIECES...

THE **UNEARTHLY** CHALLENGE TO HOLD THE SUPERHOT PLASMA MORE STABLY, BEGETS A **HUMBLER** CHALLENGE TO HOLD ITS VESSEL MORE SECURELY.

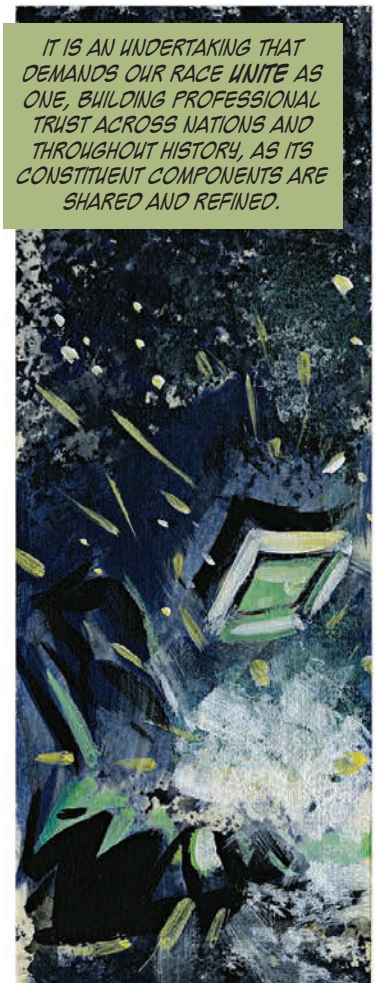
TECHNICAL STAFF AND ENGINEERS HAVE WORKED AROUND THE CLOCK TO **ARMOR** THE NSTX-U INTO A STRUCTURE OF SUPREME STATIC STABILITY...

SEIZING UPON THE CENTER STACK WITH A **MASTER'S** ABSOLUTE GRIP, REFUSING TO HEED ITS TWISTING CRIES.

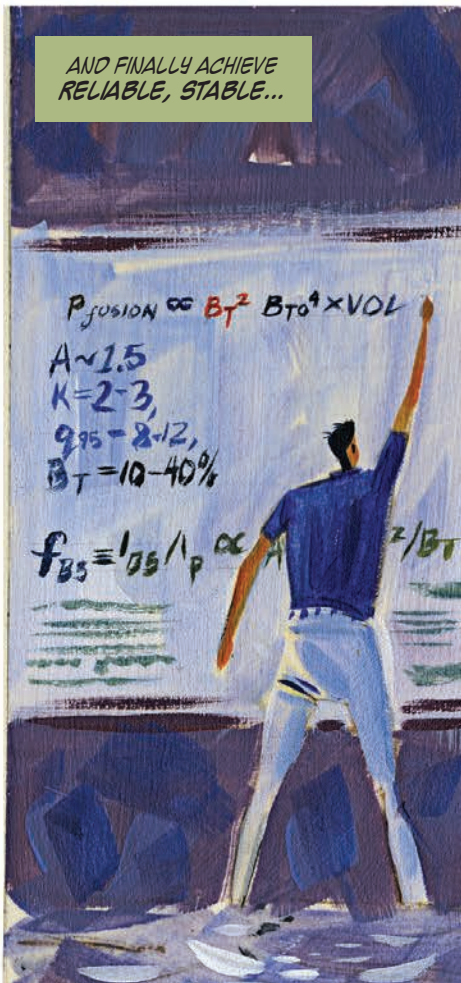

IN ADDITION, THE BRAND-NEW IS NOW COMPLEMENTED WITH THE RELIABLE: A REFURBISHED BEAMLINE FROM A 1990S PROJECT TO HEAT THE PLASMA FURTHER AND MAKE THE TRIPLE PRODUCT OF DENSITY, CONFINEMENT TIME, AND TEMPERATURE LEAP BY A FACTOR OF TEN.
NSTX-U, TOGETHER WITH OTHER TOKAMAK AND STELLARATOR EXPERIMENTS AROUND THE WORLD, ARE ADVANCING THE SCIENTIFIC THEORY NEEDED TO ENHANCE THIS CRITICAL TRIPLE PRODUCT.


MANMADE FUSION IS A MIGHTY VISION, BORN OF CREATIVE IMAGINATIONS AND UPHELD BY INTELLECTS FROM A DIVERSITY OF NATIONALITIES THAT ENCOMPASS THE US, THE EUROPEAN UNION, CHINA, JAPAN, SOUTH KOREA, INDIA, RUSSIA, AND OTHER NATIONS.


IT IS THE PINNACLE OF OUR SCIENTIFIC AND ENGINEERING DARING, SUMMONING COSMIC POWER IN SERVICE OF OUR QUOTIDIAN NEEDS.


IT IS AN UNDERTAKING THAT DEMANDS OUR RACE UNITE AS ONE, BUILDING PROFESSIONAL TRUST ACROSS NATIONS AND THROUGHOUT HISTORY, AS ITS CONSTITUENT COMPONENTS ARE SHARED AND REFINED.


IT IS THE HALLMARK OF THE SCIENTIFIC METHOD AND THE ENGINEERING PROCESS, AS OUR KNOWLEDGE OF THE FLEETING AND EXPERIMENTAL GROWS, INFORMING THEORIES TO BUILD THE OPERATIONAL.


AND FINALLY ACHIEVE RELIABLE, STABLE...
A~1.5
K=2-3,
BT =10-40%


...STEADY STATE FUSION!

“Fusion has the potential to help with all the emerging challenges of this still-new century: energy independence, national economic competitiveness, environmental responsibility and reduction of conflict over natural resources.”

Stewart Prager
Director, Princeton Plasma Physics Laboratory

“I would like nuclear fusion to become a practical power source. It would provide an inexhaustible supply of energy, without pollution or global warming.”

Stephen Hawking
Physicist and best-selling author of “A Brief History of Time”

“The challenge of global warming should stimulate a whole raft of manifestly benign innovations for conserving energy and generating it by ‘clean’ means (biofuels, innovative renewables, carbon sequestration, and nuclear fusion).”

Martin Rees
Physicist and Astronomer Royal of the United Kingdom

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