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IPNS Enriched Uranium Booster Target*

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Introduction

Since startup in 1981, IPNS at Argonne National Laboratory has operated on a fully depleted ^{238}U target. With the booster as in the present system, high energy protons to 450 MeV accelerated by the Rapid Cycling Synchrotron are directed at the target and by mechanisms of spallation and fission of the uranium, produce fast neutrons. The neutrons from the target pass into adjacent moderator where they slow down to energies useful for spectroscopy. The target cooling systems and monitoring systems have operated very reliably and safely during this period. To provide higher neutron intensity, we have developed plans for an enriched uranium (booster) target. The design effort has been underway for the past year and a preliminary design is now in hand. HETC-VIM calculations indicate that the target will produce ~ 90 kw of heat, with a nominal x5 gain (k_{eff} = 0.80). The neutron beam intensity gain will be a factor of ~ 3.

Thermal-hydraulic and heat transport calculations indicate that ^{235}U ~1/2" thick ^{235}U discs are subject to about the same tempeatures as the present ^{238}U 1" thick discs. The coolant will be light demineralized water (H_2O). The coolant flow rate must be doubled to provide adequate cooling and therefore we have designed modifications to the present cooling system. The broadening of the fast neutron pulse width should not seriously affect the neutron scattering experiments. Delayed neutrons will appear at a level about 3% of the total (currently ~ 0.5%). This may affect backgrounds in some experiments, so that we are assessing measures to control and correct for this (e.g., beam tube choppers). Safety analyses and neutronic calculations are nearing completion. Construction of the ^{235}U discs at the ORNL Y-12 facility is scheduled to begin late 1985. The completion of the booster target and operation are scheduled for late 1986. No enriched uranium target assembly operating at the projected power level now exists in the world. This effort thus represents an important technological experiment as well as being a "flux enhancer".

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Design and Operating Parameters of the Present and Booster Targets

Target	Depleted U Design Values	Present Operations	Enriched U Design Values
Incident beam	450-600 MeV protons	450 MeV protons	500 MeV protons
Repetition rate	30 Hz	30 Hz	30 Hz
Time-average proton current	22.0 μA	12-14 μA	20 μA
Target power	22.4 kW	8 kW	~ 92 kW
Total number of target discs	8	8	11
Target clad	Zircaloy-2	Zircaloy-2	Zircaloy-2
Target housing vessel	304 SS	304 SS	304 SS
Decoupler material	None	None	^{10}B - Copper
Coolant	Demin. H_2O	Demin. H_2O	Demin. H_2O
Coolant flow	45 gpm	45 gpm	90 gpm
Coolant inlet temp.	122°F	92°F	122°F
Coolant Δ temperature	3.4°F	1.2°F	~ 7.0°F
Max. temp. for 4 cm beam diameter			
at midplane of disc	598°F	94°F	539°F*
surface of disc	225°F	32°F	230°F*

*3 cm beam

Target Assembly Design Requirements and Description

The IPNS-Booster target assembly consists of an alloyed steel cylindrical housing containing zircaloy clad, uranium discs; mechanical devices to restrain the discs; coolant passages for cooling of the discs; instrumentation to monitor the condition of the target; and Boron-copper composite inserts for neutron purposes of decoupling the target from surrounding reflectors and moderators.

Radioactive products from spallation and fission are produced within the target discs. Cladding of the uranium provides for primary containment of these products. Cladding integrity will be determined by monitoring for fission product activity in the cooling system. The existing operating procedures will be used to define operating limits of radioactive contamination of the cooling system.

The target will be subject to the following proton beam conditions during normal operation:

A. The maximum power of the proton current will be a beam of 500 MeV energy and 20 μA current.

B. The proton beam will have a gaussian distribution with a minimum full width diameter at half of peak intensity of 3.0 cm.

C. The beam will be converging at the target face.

The nominal design conditions for operation at maximum proton beam power (described above) are as follows:

A. Maximum center line temperature in the uranium discs is 316°C, 600°F with the maximum differential between cooling water inlet temperature and center line temperature of the discs shall be 248°C, 478°F. The maximum surface temperature of the discs is 126.6°C, 260°F.

B. The coolant temperature differential across the target assembly is 7.0°F. The coolant inlet temperature is 50°C, 122°F.

C. The coolant flow through the target assembly is 5.67 l/S, 90 gpm.

D. The hydraulic pressure differential across the target assembly is 1.0 bar, 15 psi.

F. The maximum hydraulic design pressue of the target housing is 100 psig (corresponds to saturated steam at temperature of 170°C, 338°F).

The uranium targets have been designed to maintain cladding integrity upon loss of coolant and consequent shutdown of the proton beam. The target housing is designed to the requirements of the latest edition of "Section VIII, Div. 1" of the ASME Pressure Vessel Code. The design criteria are for the worst expected conditions. The target coolant could be light and/or heavy water. The target assembly materials will be compatible with coolant chemistry and cooling system components. Maximum surface temperature of the uranium discs will be lower than the saturation temperature of the coolant at the corresponding operating pressure.

Thermocouples inserted into six of the uranium discs sense the centerline temperature of the uranium. The thermocouple leads run through the outlet plenum and into the outlet pipe connection. The leads exit the outlet line at the top of the target extraction tunnel. The uranium discs thermocouples are 0.158 cm (0.062") O.D., 304 SS sheath, MgO insulation, type K calibration (chomel P-Alumel), ungrounded junction, and meet RDT C7-GT Standards. The target discs are secured in the containment housing with provisions for expansion based on expected expansion from all sources.

The booster target discs are made of enriched uranium metal. The total mass in all the discs is still to be determined. Stability of the uranium under proton beam irradiation is provided by additions of elemental C: +100/-200, Fe: 250 +100/-150, Si: 350 +200/-50 in weight percent. The uranium disc faces are clad in nominally 0.020 in. and on the circumference 0.030 in., welded zircaloy-2 jackets, which provide protection from corrosion. Cladding on the faces is minimized in order to consolidate the uranium. A hot isostatic pressing (HIP) operation provides metallurgical bonding between the uranium core and zircaloy-2 clad to provide adequate heat transfer. The bonding parameters should limit the grain size in the uranium to a diameter 0.02 > 0.01 cm. HIP bonding in an enert atmosphere will be controlled to prevent oxidation of the cladding. The discs are expected to remain intact under accident conditions at temperatures up to 1600°F. Decay heat analysis shows the maximum disc temperature to be ~ 1525°F under conditions of complete loss of coolant.

The discs are 4" diameter circular cylinders of two thicknesses. Edges are rounded to a 3/16" radius. Six of the targets contain 1/16" diameter clad thermo wells extending to the centerline from the edge. This provides access for thermocouples which are used for disc temperature monitoring during IPNS operation.

Each disc is supported within a 304 stainless steel container cap, which in turn is stacked within the target housing. The container caps are restained by radial arc cuts in the housing wall. Rotation of the caps is prevented by means of tabs mounted on the container caps. Axial restraint of the disc stack is provided by a spring loaded stainless steel spring assembly located at the back of the housing. Spring material is Inconel 600.

Coolant is supplied and returned through pipe connections located at the back of the target. Channeling in the back of the target housing directs flow to and from the inlet and outlet plenums. The inlet and outlet plenums are formed between the housing walls and the container caps. The container caps' ends are slotted and form parallel flow ducts which connect inlet and outlet plenums when discs and caps are assembled and stacked in the housing. Cooling of the discs' faces is by forced convection in these ducts. An accurate small clearance fit between the container caps and radial arcs machined in the housing walls prevents short circuiting of the coolant around the caps.

The container caps provide support for the source discs and form ducts for coolant flow at the disc face. Each of the source discs is installed in a container cap. The caps are similar except for length and flow area of the ducts. A slot is provided for installation of thermocouples in some of the discs.

Radial support of the source discs is effected by containment within the cylindrical portion of the caps. A radial clearance of 0.007 in. between disc and cap is provided to allow for disc expansion. This design clearance is based on an expected total lifetime expansion of 1.5% of the radius. Axial restraint of the discs is provided by the flat spacers at the end of the caps. A spring loaded assembly at the end of the disc stack causes contact pressure between spacers and disc face.

Rectangular flow ducts are formed between the disc spacers and disc faces. The duct depth (dimension in the axial direction) is determined by the spacer thickness and is equal to 0.063 in. This dimension has been minimized in order to consolidate the uranium. Duct width (dimension in the radial direction perpendicular to the flow) varies with the duct length and is determined by thermal and hydraulic considerations and varies from disc to disc according to the heat flux at the cooled surfaces.

The spring support housing subassembly provides an axial restraint force on the disc stack, and coolant flow separation between inlet and outlet pleniums in the target housing. A boron-copper composite disc is installed toward the front of the spring housing for neutron decoupling purposes.

Axial restraint on the disc stack is provided by a spring loaded backup disc located at the back of the housing. Two concectric Inconel 600 coil springs, each of which is capable, by itself, of providing sufficient axial compression (100 pounds) to restrain the disc stack, are installed behind the back-up disc and cause a separation force between the back-up disc and the front end of the flow distribution chamber. The spring force applied to the front end of the flow distribution chamber pushes this chamber against the back of the target housing while the opposing spring force on the back-up disc is applied to the disc stack. The disc retaining caps are free to move axially along the slides mounted in the target housing, allowing the spring force to be transmitted to each disc face. Since the length of the retaining caps is slightly less than the source disc length, contact between the spacers and the disc faces is assured. The spring force of either spring provides sufficient restraint of the discs to prevent movement during target handling and from hydraulic forces during operation of the target cooling system, but the total spring force does not cause excessive stress concentrations on the disc faces or inhibit final closure of the target housing. Maximum spring deflection and the associated clearances provide for a total lifetime expansion of 2.6% of the total uranium length. the target housing is of welded construction, fabricated entirely of 304 stainless steel.

The target housing provides the containment for the coolant in the target assembly, support for the container caps and spring support subassembly. Also, a layer of Boron-copper composite material is installed in the housing shell for neutron decoupling purposes.

Support of the caps and spring support housing is provided by direct contact with the housing wall. Radial arcs machined in the housing wall at these contact points provide an accurate fit between retaining caps, spring support housing and the housing wall. Axial restraint of the disc stack is effected by direct contact with the front and back walls of the housing. Final closure of the target housing (weldment of the back wall) deflects the compression spring, thereby spring loading the disc stack.

Target Cooling System Modifications

Fission and spallation of the enriched uranium produce a substantial amount of heat requiring temperature sensing and forced convection cooling to assure satisfactory operation of the target

The increased operating thermal power of the booster target will add ~ 68 kilowatts over the original IPNS-I target design. This increase in thermal power will require twice the primary coolant flow (45 gpm to 90 gpm). To accomplish this, modifications to the two independent cooling systems (Neutron Scattering Target and Radiation Effects Target) will be made for parallel operation. Design considerations will also be given to keep intact the radiation effects cooling system, so that it can be operated if the need arises.

Each cooling system supplies 2.8 l/s (45 GPM) for total flow of coolant of 90 GPM to the target assembly. Total pressure drop across the target assembly at design flow is 1.0 Bars, (15 psi) with a minimum static pressure in the target assembly of 2.4 Bars, (35 psia). Coolant is demineralized light or heavy water with a target inlet temperature of 50 C, (122°F). All wetted parts in the cooling systems are chemically compatible with zircaloy-2 and 304 stainless steel. In order to prevent blockage of flow ducts from solids in the coolant a 3 micrometer* sintered stainless steel in line after filter and a 0.45 micrometer* prefilter are installed in each cooling system. (The minimum width of the flow ducts is 0.16 cm), (1/16"). (* - rated absolute removal in liquids.) Certain sections of the piping will be increased in diameter and the flex-hose will be increased from 1 1/4" to 2" diameter. A pressure relief valve for the target housing will be provided to protect the housing in case of a loss of coolant incident. Due to the increased diameter of the hose a new target linkage and hose connection assembly was is needed. Due to the corrosion problems with the present linkage assembly, the material for the new linkage will be a material (probably stainless steel) to minimize the formation of rust. This should reduce loose contamination problems during maintenance periods.

Tests performed on the present heat exchangers indicate they are adequate for the increased heat load.

The increased decay heat requires maintaining a low coolant flow after operation. Two new smaller pumps will be installed for this purpose. These pumps will be powered by a uninterruptable power supply.

The instrumentation, controls and alarm/shutdown modifications are minimal. Two additional thermocouples and associated instrumentation will be added to the present system. One total primary target flow meter and two decay heat flow meters will be installed. Certain controls and safety interlocks will also be revised.

Reflector Assembly

The target assembly is installed in a graphite reflector assembly cavity. The cavity has the same cross sectional configuration as the target housings with allowance for 0.159 cm, (1/16"), clearance all around. The maximum travel of the target into the cavity is 55.25 cm, (21.75"), from front face of housing to entrance of cavity. The cavity bore tube also contains a Boron-copper composite for neutron decoupling purposes.

Coolant and Reflectors

Cost considerations led us to choose a graphite reflector and light water (H_2O) coolant. The table shows the pulse width from the target with heavy water (D_2O) and beryllium alternatives.

For $k_{eff} = 0.80$ and nominal gain G=5, and with 1.2×10^{22} $^{10}B/cm^2$ decoupling around the target and lining the proton tunnel. We compute the booster pulse width as the product of the gain times the prompt neutron generation time, $\tau = Gl$.

	H_2O	D_2O
Graphite reflector	5 x 68 = 340 nanosec	5 x 51 = 255 nanosec
Beryllium reflector	5 x 62 = 310 nanosec	5 x 43 = 215 nanosec

The results show that the beryllium/D_2O combination is the optimum. Our design goal was a pulse width of less than 500 nanoseconds.

Replacing the light water (H_2O) with heavy water (D_2O) will generally reduce k_{eff} by 0.010 or 0.015 (e.g., from 0.80 to 0.79 or 0.785).

Replacing a graphite reflector with a beryllium reflector will generally increase k_{eff} by 0.020 or 0.025 (e.g., from 0.80 to 0.82 or 0.825).

Analysis Summary

The thermal-hydraulic, thermal-stress and off normal conditions analyses should be completed in the near future.

Mechanical design analysis consist of the following:

- Thermal/Hydraulic Analysis
  - Cooling System Hydraulics
    - Model existing system (hydraulic code)
    - Field tests
    - Compare & adj. model
    - Model revised system (hydraulic code)
    - Run cases
      - (a) 2-pumps running (normal)
      - (b) 1-pump running (off normal)
      - (c) Broken spring case (off normal)
      - (d) Blocked channel cases (off normal)
      - (e) Parametric study-variable resistances & pump curve (normal)
  - Disc Thermal Analysis
    - Model 1" disc (ANSYS Code)
    - Model 1/2" disc (ANSYS Code)
    - Cases
      - (a) Find worst case disc for given Q & H (normal)
      - (b) Broken springs case (off normal)

(c) Blocked channel cases (off normal)

(d) Insulating effect of space (normal)

(e) Parametric study-variable Q & H (normal)

Q = Energy Deposition Rate
H = Convective Film Coefficient

Determine transient response of disc

Margin to Channel Boiling Analysis

Decay Heat Analysis (all off normal)

Stoppage of primary coolant flow

Stoppage of secondary coolant flow

Loss of coolant in target (THTB Code)

Target Handling System

The target handling system provides the mechanism for installation of the target assembly into the reflector cavity. The handling system consists of a linkage train and a curved passage way (extraction tunnel) through the shielding.

The maximum target assembly length from the front face of the housing to the first linkage pivot is 32.86 cm, (12.94"). The ovrall cross sectional dimensions of the target assemblies are 13.65 cm, (5.375") by 11.11 cm, (4.375"). This geometry allows for adequate clearance between target assemblies and the curved extraction tunnels.

The transition link is connected to the target assembly by mounting lugs machined in the housing back plate. The transition link is designed for a pull force of 3000 lbs. at the target assembly. The target housing is designed to withstand an external loading equal to or greater than the 3000 lb. pull force. However, the design internal pressure loading of 100 psig and the pull force loading cannot be applied simultaneously.

IPNS Facility Shielding Changes

A review of the IPNS monolith shielding was conducted and the changes required are minor. Recommendations were adding shielding to cover the neutron beam gate drive housings and additional shielding in some areas by the target coolant housings.

There is no increase in groundwater activation to be expected from the operation of the booster target. This is because there is no increase in the intensity of the incident 500 MeV proton beam, which produces the high energy spallation neutrons which are the only ones that can reach the soil.

The booster target has only the effect of producing additional fission neutrons having energies not higher than a few MeV. These neutrons are slowed down by the 5 feet thick steel shield under the target to about 20 KeV (iron window neutron energy). Below the steel shield is a 3 feet thick concrete slab which is sufficient to absorb the iron window neutrons.

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